THE QUATERNARY ERA

WITH SPECIAL REFERENCE

TO

ITS GLACIATION

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By

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KEY TO ABBREVIATIONS OF TITLES OF PERIODICALS

Publications of societies and institutions have generally long titles. With few exceptions these have been greatly reduced in the references at the ends of chapters and in the Bibliography at the end of the work.

The general abbreviations used (unless modified in the list of publications set out below) are the following:

A.	*Association*
Ab.	*Aarbog*, etc.
Abh.	*Abhandlung*
Am.	*American*
Ann.	*Annals*, etc.
Ark.	*Arkiv*
B.	*Bulletin*, etc.
BB.	*Beilage Band*
Bbl.	*Beiblatt*
Bd.	*Band*
Bh.	*Beiheft*
Bot.	*Botanical*, etc.
Btr.	*Beiträge*
C.	*Congress*
CR.	*Comptes Rendus*
D.	*Deutsch.*
Erg.	*Ergänzungs.*
Erl	*Erläuterung*
FC.	*Field Club*
Fbd.	*Festband*
Fschr.	*Festchrift*
G.	*Geology*, etc.; *Gesellschaft*
Gg.	*Geography*, etc.
Gl.	*Glacial*, etc.
Gphys.	*Geophysik*
H.	*Heft*
Hb.	*Handbuch*
I.	*Institute*, etc.
int.	*international*, etc.
J.	*Journal*
Jb.	*Jahrbuch*
JB.	*Jahresbericht*
K.	*Karte*
Lb.	*Lehrbuch*
Lk.	*Landeskunde*
M.	*Mitteilung; Medd.*
Mo.	*Monthly*
nf.	*Naturforschung*
nh.	*Naturhistorisch*
nk.	*Naturkunde*
Nschr.	*Naschschrift*
nw.	*Naturwissenshaft*, etc.
P.	*Proceedings; Paper; Publication*
Pal.	*Palaeontological*, etc.
Ph.	*Philosophical*, etc.
PP.	*Professional Paper*
R.	*Review*, etc.
RC.	*Rendiconti*
Rp.	*Report*
S.	*Society*, etc.
SB.	*Sitzungsbericht*
Sbd.	*Sonderband*
Sc.	*Science*, etc.
Schr.	*Schriften*
Sv.	*Survey*
T.	*Transactions*
U.	*University*, etc.
Un.	*Union*
V.	*Verein*
Ver.	*Veröffentlichung*
Vh.	*Verhandlung*
vl.	*vaterländisch*
Z.	*Zeitschrift*
Zbl.	*Zentralblatt*

The titles of journals, etc., frequently used, have been much reduced. The more important abbreviations are set out below, the contractions on the right of the page being those sanctioned in the *World List of Scientific Periodicals* compiled by the World List Association (Ed. 3, 1952). For further abbreviations to the references, see p. xvii.

A. J. S.	*Amer. J. Sci.*
Abh. bayer. Ak.	*Abh. bayer. Akad. Wiss. Maths. Phys. Kl.*
Abh. Gg. G. Wien	*Abh. geogr. Ges. Wien*
Abh. LA.	*Abh. preuss. geol. Landesanst. New Folge. Berlin*
Abh. preuss. Ak.	*Abh. preuss. Akad. Wiss.*

Act. S. Helv.	*Verh. Schweiz. naturf. Ges.*
Am. G.	*Amer. Geol.*
Ann. G.	*Ann. Géogr.*
Ann. Hydr.	*Ann. Hydrogr. Berl.*
Ann. Mag.	*Ann. Mag. nat. Hist.*
Ann. N.Y. Ac.	*Ann. N.Y. Acad. Sci.*
Ann. Obs.	*Ann. Obs. Mont Blanc.*
Ann. Phys.	*Ann. Phys. Lpz.*
Ann. S. G. N.	*Ann. Soc. géol. Nord*
Ant.	*Antiquity*
Anthr.	*Anthropologie. Paris*
Appal.	*Appalachia*
Arch.	*Archaeologia*
Arch. I. P. H.	*Arch. Inst. Paléont. hum.*
Arch. M. N.	*Arch. Math. Naturv.*
Arch. Meckl.	*Arch. Ver. Naturg. Mecklenb.*
Arch. Sc.	*Arch. Sci. phys. nat.*
Arch. Teyl.	*Arch. Mus. Teyler.*
Ark. Kemi.	*Ark. Kemi Min. Geol.*
B. A. Gg. S.	*Bull. Amer. geogr. Soc.*
B. Ac. imp.	*Bull. Acad. Sci. St.-Petersb.*
B. Ac. Pol.	*Bull. int. Acad. Cracovie (Cl. math. nat.)*
B. C. G. Petersb.	*Bull. Com. geol. St.-Petersb.*
B. S. belg. G.	*Bull. Soc. belg. Géol. Pat. Hydr.*
B. S. G. F.	*Bull. Soc. géol. Fr.*
B. S. nat. Mosc.	*Bull. Soc. Nat. Moscou*
B. S. neuch.	*Bull. Soc. neuchâtel Sci. nat.*
B. S. Vaud.	*Bull. Soc. vaud. Sci. nat.*
Ber. nf. G. Freib.	*Ber. naturf. Ges. Freiburg. i. B.*
Ber. sächs. Ak.	*Ber. sachs. Ges. Akad. Wiss. math. phys. Kl.*
Bih. Sv. Ak. H.	*Bih. Svensk Vetensk Akad. Handl.*
Boston S. Occ. P.	*Occ. Pap. Boston Soc. nat. Hist.*
Boston S. P.	*Proc. Boston Soc. nat. Hist.*
Bot. Not.	*Bot. Notiser.*
Btr. G. K. Schw.	*Beitr. geol. Karte Schweiz.*
C. Min.	*Zbl. Min. Geol. Paläont.*
Can. Mus. B.	*Mus. Bull. geol. Surv. Can.*
Can. Mus. Mem.	*Mus. Mem. geol. Surv. Can.*
Can. Rp.	*Ann. Rept. new ser. geol. Surv. Can.*
CR.	*C. R. Acad. Sci. Paris*
CR. C. Arch.	*Congr. int. Anthrop. Archeol. prehist.*
CR. C. G.	*int. géol. Congr.*
CR. C. Gg.	*int. géogr. Congr.*
D. Boden.	*Dtsch. Boden*
D. G. U.	*Danm. geol. Unders.*
Dschr. Ak. Wien	*Denkschr. Akad. Wiss. math. naturw. Kl.*
E.	*Eiszeit (u. Urgeschichte)*
E. & G.	*Eiszeitalter u. Gegenwart*
Ecl.	*Ecl. geol. Helv.*
Essex N.	*Essex Nat.*
Étud. gl.	*Étud. glaciol.*
F.	*Fennia*
F. F.	*Forsch. Dtsch. Wiss. Fortschr.*
F. G. P.	*Fortschr. Geol.*
F. Lk.	*Forsch. Dtsch. Landesk.*
Finl. B.	*Bull. Comm. géol. Finl.*

G.	*Geologist.*
G. Abh.	*Geogr. Abh.*
G. Ann.	*Geogr. Ann. Stockh.*
G. Anz.	*Geogr. Anz.*
G. Charb.	*Geol. Charakterbilder*
G. F. F.	*Geol. Foren. Stockh. Förh.*
G. F.	*Geogr. J.*
G. JB.	*Geogr. Jber. Öst.*
G. M.	*Geol. Mag.*
G. Mijnb.	*Geol. en. Mijnb.*
G. Pal. Abh.	*Geol. Paläont. Abh. Jena.*
G. R.	*Geogr. Rev.*
G. Rd.	*Geol. Rdsch.*
G. S. A. B.	*Bull. geol. Soc. Amer.*
G. S. A. Mem.	*Mem. geol. Soc. Amer.*
G. S. A. Spec. P.	*Spec. Pap. geol. Soc. Amer.*
Gfys. P.	*Norsk. Vidensk. Ak. Geofys. Publikasjoner*
G.	*Géographic*
G. T.	*Geogr. Tidsskr.*
Gl. M.	*Glacialists' Mag.*
Him. J.	*Himalayan J.*
I. N.	*Irish Nat.*
I.N.J.	*Irish Nat. J.*
Ind. Mem.	*Mem. geol. Surv. India*
Ind. Rec.	*Rec. geol. Surv. India*
INQUA	*Int. Assoc. Study Quaternary*
J. Conseil.	*J. Conseil int. Explor. de la Mer*
J. G.	*J. Geol.*
J. G. S. Dubl.	*J. Geol. Soc. Dubl.*
J. Gl.	*J. Glaciol.*
J. LA.	*Jb. preuss. geol. Landesanst.*
J. RA(BA)	*Jb. geol. Reichsanst. (Bundesanst.), Wein*
J. R. A. I.	*J. R. anthrop. Inst.*
J. R. G. S. Ire.	*J. Roy. Geol. Soc. Ireland. Dubl.*
J. S. AC.	*Jb. schweiz. Alpenkl.*
Leop.	*Leopoldina. Halle*
M. Bad. LA.	*Mitt. bad. geol. Landesanst.*
M. D. G. F.	*Medd. dansk. geol. Fören.*
M. D. O. AV.	*Mitt. ditsch. ost. Alpenver.*
M. Gr.	*Medd. Gronland*
Manchr. Mem.	*Mem. Manchr. lit. phil. Soc.*
Matér.	*Matér. Étude de l'Homme*
Matér. Étud. Cal.	*Matér. Étud. Calam.*
Mém. Ac. imp.	*Mém. Acad. Sci. St.-Petersb.*
Mich. Ac. P.	*Mich. Acad. Pap.*
Mo. W. R.	*Mon. Weath. Rev. Wash.*
Mus. C. Z. B.	*Bull. Mus. comp. Zool. Harv.*
Mus. C. Z. Mem.	*Mem. Mus. comp. Zool. Harv.*
N.	*Nature, Lond.*
N. Dschr.	*N. Denkschr. schweiz. naturf. Ges.*
N. G. T.	*Norsk. geol. Tidsskr.*
N. G. U.	*Norsk. geol. Unders.*
N. J.	*N. Jb. Min. Geol. Paläont.*
N. Ph. J.	*Edinb. New. Phil. J.*
Nat.	*Naturen*
Nat. G. M.	*Nat. geogr. Mag.*

Nat. Mus.	*Natur u. Mus.*
Nat. Volk	*Natur u. Volk*
Njahrsbl.	*Naturforsch. Ges. Zurich, Neujahrsbl.*
Nschr. G. Gött.	*Nachr. Ges. Wiss. Göttingen*
Nw.	*Naturwissenschaften*
Nw. Wschr.	*Naturw. Wschr.*
N.Y. Mus. B.	*Bull. N.Y. St. Mus.*
Nyt. M.	*Nyt. Mag. Naturv.*
Ö. Vet. Ak. F.	*Öfvers. Ventensk. Akad. Förh. Stockh.*
Ostalp. Fst.	*Ostalpine Formenstudien*
P. A. A.	*Proc. Amer. Ass. Adv. Sci.*
P. Austr. A.	*Proc. Austral. Ass. Adv. Sci.*
P. G. A.	*Proc. Geol. Ass.*
P. Lpl. G. S.	*Proc. Lpool. geol. Soc.*
P. M.	*Petermanns Mitt.*
P. P. S.	*Proc. prehist. Soc.* (earlier, *Proc. Prehist. Soc. E. Anglia*)
P. Phys. S.	*Proc. R. Phys. S. Edinb.*
P. R. D. S.	*Proc. R. Dubl. Soc.*
P. R. G. S.	*Proc. R. Geogr. Soc. Lond.*
P. R. I. A.	*Proc. R. Irish Acad.*
P. R. S.	*Proc. roy. Soc.*
P. R. S. E.	*Proc. roy. Soc. Edinb.*
P. Roch. Ac.	*Proc. Rochester Acad. Sci.*
P. Spel. S.	*Proc. Speleol. Soc. Bristol*
P. Y. G. S.	*Proc. Yorks. geol. (polyt.) Soc.*
Pal.	*Palaeontographica*
Pal. Z.	*Palaeont. Z.*
Ph. M.	*Phil. Mag.*
Ph. T.	*Phil. Trans.*
Pr. Z.	*Prähist. Z.*
Q.	*Quartär*
Q. J.	*Quart. J. geol. Soc. Lond.*
Q. J. R. M. S.	*Quart. J. R. met. Soc.*
Qper.	*Quartärperiode*
R. G.	*Rev. Géogr. (annu.) Paris*
R. Hydr.	*Int. Rev. Hydrbiol.*
Rp. B.A.	*Rep. Brit. Ass.*
S. G. F.	*Samml. geol. Führ.*
S. G. M.	*Scot. geogr. Mag. Edinb.*
S. G. U.	*Sverig. geol. Unders. Afh.*
SB. Ak. Wien	*SB. Akad. Wien, math. naturw. Kl.*
SB. bayer. Ak.	*SB. bayer. Akad. Wiss.*
SB. heidelb. Ak.	*SB. heidelb. Akad. Wiss. math. naturw. Kl.*
SB. preuss. Ak.	*SB. preuss. Ak. Wiss. math. physl. Kl.*
SB. sächs. Ak.	*SB. sächs. Ak. Wiss. math. phys. Kl.*
Sc.	*Science (new series)*
Sc. Pr.	*Sci. Progr. Twent. Cent.*
Sc. P. R. D. S.	*Sci. Proc. R. Dubl. Soc.*
Sc. T. R. D. S.	*Sc. Trans. R. Dublin Soc.*
Schr. phys. ök. G.	*Schr. phys.-ökon. Ges. Königs.*
Senckenb. Abh.	*Abh. Senckenb. naturf. G.*
Senckenb. Ber.	*Ber. Senckenb. anturf. G.*
Sm. Ctr.	*Smithson. Contr. Knowl.*
Sm. Misc. C.	*Smithson. Misc. Coll.*
Sm. I. Rp.	*Smithson, Inst. Rep.*
Sv. Mem.	*Mem. Geol. Surv. U.K.*

Svalb. M.	*Svalb. og Ishavet Medd.*
Svalb. Skr.	*Skr. Svalb. og Ishavet.*
T. E. G. S.	*Trans. Edinb. geol. Soc.*
T. G. S. Glasg.	*Trans. geol. Soc. Glasg.*
T. N. Z. I.	*Trans. Proc. New Zeal. Inst.*
T. R. I. A.	*Trans. R. Irish Acad.*
T. R. S. Can.	*Trans. roy. Soc. Can.*
T. R. S. E.	*Trans. roy. Soc. Edinb.*
T. R. S. N. Z.	*Trans. roy. Soc. New Zeal.*
Tijds.	*Tijdschr. ned. aardrijksk. Genoot.*
Ups. B.	*Bull. geol. Instn. Univ. Upsala*
U.S. G. S. B.	*Bull. U.S. geol. Surv.*
U.S. G. S. M.	*Monogr. U.S. geol. Surv.*
U.S. G. S. PP.	*Prof. Pap. U.S. geol. Surv.*
U.S. G. S. WSP.	*Wat.-Supp. (Irrig.) Pap. Wash.*
V. M. N. F.	*Vidensk. Medd. naturh. Foren. Kbh.*
Ver. I. Meeresk.	*Veröff. Inst. Meeresk. Univ. Berl.*
Ver. Rübel I.	*Veröff. geobot. Ges. Rübel*
Vet. Ak. H.	*K. svenska Vetensk. Akad. Handl.*
Vh. Ak. Wet.	*Verh. Akad. Wet. Amst.*
Vh. G. E.	*Verh. Ges. Erdk. Berl.*
Vh. Gen. Ned. Kol.	*Verh. geol-mijnb. Genoot. Ned. Kol.*
Vh. GTag.	*Verh. dtsch. Geogr. Tag.*
Vh. RA.	*Verh. geol. ReichsAnst. (StAnst.) Wien*
Vid. Selsk. F.	*Forh. Vidensk. Selsk. Krist.*
Vid. Selsk. Skr.	*Skr. norske Vidensk. Akad.*
Vjschr.	*Vjschr. naurf. Ges. Zürich*
Württ. Jh.	*Jh. Ver. vaterl. Naturk. Württemb.*
Y.	*Ymer.*
Z. AV.	*Z. dtsch. öst. Alpenver.*
Z. D. G. G.	*Z. dtsch. geol. Ges.*
Z. G. E.	*Z. Ges. Erdk. Berl.*
Z. G. E. Lpz.	*Z. Ges. Erdk. Lpz.*
Z. Gf.	*Z. Geschiebeforsch.* (*u. Flachlandsgeologie* after 1935)
Z. Gl.	*Z. Gletscherk.*
Z. Gl. Gl.	*Z. Gletscherk. u. Glacialgeol.*
Z. Gm.	*Z. Geomorph.*
Z. Nw.	*Z. Naturw.*
Z. pr. G.	*Z. pract. Geol.*
Zoogr.	*Zoogeographica*

To shorten the references still further, the following types have been uniformly adopted: Series (n.s., N.F., etc.) are in Roman type; part, number, Teil, fascicule are in brackets; volume, year and page (the page in the vast majority of cases refers to the exact page where the statement referred to is made) are in ordinary type and in this order. Where, as in the case for example of the *Neues Jahrbuch für Min.*, etc., more than one volume is issued per annum, the number of the volume is given in Roman numerals after the year, e.g. *N. J.* 1900, II, 89.

Where only a number in italics is given, usually followed by a page number, the reference is to a publication listed in the Bibliography at the end of the work. When this publication has more than one volume, the number is put in Roman numerals—*1485*, III, 289 is H. B. de Saussure, *Voyages dans les Alpes*, vol. 3, p. 289. When it has more than one edition the number of the edition is given in brackets—*591* (3) is J. Geikie, *Great Ice*, Ed. 3.

TEXT ILLUSTRATIONS AND THEIR SOURCES

(For italicised numbers, see p. xvii; for contractions, see pp. xiii-xvii)

PLATES

PART III

THE QUATERNARY ERA

Chapter XXIX

VOLCANIC AND TECTONIC ACTIVITY

1. *Terminology*

The short-lived period after the Pliocene (some authors[1] would prolong the Pliocene into the present) Lyell[2] designated Post-Pliocene or Newer Pliocene. The term Quaternary, now generally current, was introduced as *Quaternaire* by J. Desnoyers[3] for the Paris Basin in 1829 and four years later by H. Reboul[4] for faunal reasons—the spelling should be "Quarternary" as suggested by A. Morlot[5] (*Quartaire*) and used in Denmark (*Kvartaer*) and Holland (*Kwartair*) and in the equivalent *Quartär* which German geologists, following C. F. Naumann, have employed. All the logical arguments, however, are against its use and favour the word Pleistocene[6] (Gr. *Pleistos*, most; *Kainos*, new), the subdivision of the Tertiary which Lyell[7] made in 1839 though subsequently[8] (1863) suggested should be abandoned because of the different meanings attached to it.

The term Quaternary conveys an entirely false conception of the magnitude of the changes that closed the Pliocene. The Pliocene and Pleistocene blended almost imperceptibly; the tectonic processes of the Tertiary continued into the Pleistocene; the changes in the distribution of land and sea were of minor import; and the flora and fauna (marine, land, vertebrate and invertebrate) underwent no radical modification—their relations are so close and their forms so commonly specifically identical that seemingly no line of division can be drawn which is not arbitrary (see below). This is particularly true of the plants.

The period's significance in the time-scale is also exaggerated, since it ranks in no way with the preceding eras in its length (see ch. L) or in the thickness of its sediments (see p. 222)—the *c.* 200 m (unbottomed) in the Russian Altai,[9] *c.* 213 m at Fort Nelson,[10] over 240 m in the southern peninsula of Michigan,[11] over 300 m in the Seneca and Onondaga valleys of west-central New York,[12] *c.* 366 m at New Orleans,[13] over 600 m on the floor of Lake Bonneville,[14] 700 m, 760 m or 900 m in California,[15] *c.* 676 m in the area of the Fraser delta,[16] 861·5 m (unbottomed) at Tientsin,[17] more than 1220 m in the Albert Rift of East Africa,[18] *c.* 1830 m discovered at Ventura in California[19] (the greatest thickness of Pleistocene yet known), are quite exceptional.

The justifications for a fourth era are first, the appearance of man who has greatly modified and must in the future still more profoundly modify the fauna and flora of the earth (see below); and secondly, the glaciation which has left its stamp upon the earth. But the era, though often styled the Age of Man (obvious alternatives are Psychozoic,[20] Anthropozoic,[21] Anthropogene[22] or Anthropéian[23]—Adolescian has been suggested for post-Villafranchian[24]) whose appearance and development, it has been suggested, may have been linked with these physical changes, may not have co-extended with his range. Many archaeologists postulate a Tertiary man (see p. 832). Similarly, glaciers may have appeared somewhat late in the

Quaternary,[25] for the interval between the Pliocene and the first glaciation, often loosely styled "preglacial" and termed Ozarkian,[26] was long: it contained the "preglacial terraces" of Germany (see p. 919), the Donau glaciation (see p. 937) and the ascending series of glacial advances (see pp. 701, 920). In Italy[27] the sea-level fell from c. 200 m in the Calabrian to c. 100 m in the Sicilian by five stages and was accompanied by a very considerable denudation of land-surfaces—the Villafranchian in Upper Val d'Arno is c. 150 m thick and the Calabrian is far thicker than the total Pleistocene deposits or postpliocene.[28] Alternatively (and somewhat doubtfully[29]) glaciers may have appeared during the Pliocene, as asserted for the Alps,[30] Pyrenees,[31] Vosges,[32] Black Forest,[33] Auvergne,[34] north Germany and Holland,[35] Iceland,[36] south Russia,[37] Caucasus,[38] Pamirs,[39] Siberia,[40] Alaska,[41] Mount Rainier,[42] New Zealand[43] and Antarctica[44] (cf. p. 307), or even during the Miocene in France, New Zealand and the Alps[45]—this pre-Quaternary phase of the glaciation has been termed the Polycene.[46] Stress is laid on the late appearance of a faunal change (see p. 1031). Cold mammalia were present in the Cromerian (see p. 995), the First Pluvial epoch occurred during the upper Pliocene,[47] and the coldest seas marked the close of the Pleistocene (see ch. XXXVI). Not only the Günz[48] but the Mindel glaciation[49] is relegated to the Pliocene (the *Deckenschotter* preceded the marine Plaisancian and had no Pleistocene molluscs[50]); and the Norwich and Weybourne Crags are bracketed with the first two glaciations.[51] Two Pliocene glaciations have been postulated for the Ukraine[52] and the Nebraskan and Kansan glaciations have also been placed in the Tertiary.[53] In any case, the existence of widespread glaciation in earlier times, e.g. Permo-carboniferous, was not used to create separate periods at such times.

Despite these forceful contentions, the word Quaternary is almost universally employed and probably will continue to be so used for its convenience if not for its scientific value. World-wide glaciation and the development of man are outstanding events.

The Pleistocene period and the Ice Age were coeval, as E. Forbes[54] suggested in 1846. They do not, however, embrace Lyell's Holocene or Recent period[55] (the current use of this term, accepted by Lyell in 1873, dates from Forbes,[56] since in Lyell's original classification[57] Recent included what is Pleistocene plus Recent) or the *Alluvium* of W. Buckland and German geologists which some would elevate into a fifth or *Quintinaire* era.[58] This last proposal is unjustifiable, even when every allowance is made for the impressive consequences of man's interference with Nature,[59] both physical and biological: the largest animals are disappearing, smaller creatures are multiplying beyond aboriginal numbers and "foreign" creatures are spreading and creating a degree of cosmopolitanism throughout the world's fauna.

The name "Glacial period" connoting glaciers came into use about 1840 after Agassiz had called attention to their former existence in Britain (see ch. XXX). Since glaciers appeared and disappeared at different times and vanished during the long interglacial epoch or epochs which lasted more than half the total period (see p. 919), Pleistocene is preferable as a general term, though climate does probably play a major role in its definition.[60]

Plio-Pleistocene boundary. Diastrophism and vulcanicity, which have furnished criteria for classification and correlation of geological datum history, were not sufficiently universal at the beginning of the Pleistocene to be used as a datum line, though they occurred round the Pacific Ocean, including the

geosynclinal area of south California,[61] the Rocky Mountain region[62] and the Philippine Islands.[63] They also took place in Asia from the Caucasus to central and eastern Asia,[64] including China (see p. 605), and in India[65] where Upper Siwalik beds with a Villafranchian fauna, including horse, elephant and primitive cattle, lie disconformably on Middle Siwalik strata yielding a Pontian fauna (see below) but are themselves succeeded by a period of intense folding and planation (see p. 605). In Burma[66] too a major structural break and angular unconformity, due to folding, tilting and faulting, exists between the Lower and the Upper (Villafranchian) Irrawaddy divisions. An unconformity, coupled with the extinction of marine molluscs, can rarely, as in Morocco,[67] Italy,[68] New Zealand[69] (see below), New Guinea[70] or western North America,[71] be recognised since marine upper Pliocene deposits cover very small areas. Moreover, no reference sequence is known to which the local fauna and flora can be referred, nor can any climatic happening be detected. In the terrestrial Idaho formation of North America the fossil plants have a Pliocene, the animals a Pliocene and Pleistocene aspect.[72] In many other extraglacial lands,[73] e.g. Hungary, Egypt, South and East Africa, India, East Indies, South America, Australia and Tasmania, and even in the Paris Basin where Lyell created the name Pleistocene period (see above), the Pliocene passes insensibly into the Pleistocene: the very thick deposits preserved in the north-west Sub-Himalayas show no definite natural break at this horizon.[74] The same rivers drained the land, the same seas beat against the shore. A dividing line hardly exists, and beds are only referable to the Plio-Pleistocene. In Iceland, the boundary lies deep in the basalt mountains.[75] Even in glaciated lands it is very debatable. Thus the St. Prestian is placed in the upper Pliocene,[76] the Plio-Pleistocene transition (M. Boule) or the First Interglacial[77]; the Villafranchian, formerly widely regarded as Pliocene, has been placed in the Pleistocene[78] (see below); and the Mammaliferous clays and lignites of Leffe[79] in the Alps of Bergamo are classed with the upper Pliocene,[80] preglacial,[81] First interglacial or Cromerian.[82] The age of the Tiglian is similarly disputed (see p. 1044) and the fossil molluscs of the East Anglian Crag suggest Pliocene though remains of elephant, horse and ox make it early Pleistocene (see below). In south California, with its thick Pliocene-Pleistocene sequence, disagreement as to the position of the boundary is complete,[83] yet teeth of *Equus* have been found in the Santa Barbara formation and in the San Pedro formation of the Ventura basin. In New Zealand the boundary lies within the Wanganui Series and the record is continuous from the Tertiary into Recent (Cotton, 1954, 1955).

The Upper Siwalik of India is placed in the upper Pliocene or the early Pleistocene though the Pinjor fauna[84] is clearly equivalent to the European Villafranchian[85] (see p. 1052)—*Elephas planifrons* occurs in both. Nevertheless, in north China[86] (see p. 545) a definite faunal and physiographic break is recognisable in the Sanmenian between the Nihowan (Villafranchian) stage of deposition and the beginning of the following Choukoutien sedimentation (lowest Pleistocene) and is chosen as the base of the Pleistocene by the Cainozoic Research Laboratory[87]—the change corresponded to a positive movement rejuvenating the entire Pliocene topography—though the Nihowan or Sanmenian has been placed in the lower Pleistocene.[88] In Java, the boundary is placed between the Kali Glagah and the Djetis horizons[89] (see p. 1052).

The passage from Pliocene to Pleistocene is therefore almost perfect; the

latter in its mammals, molluscs and plants chronicles merely the climax of the cold foretold in the later Tertiary (see p. 690). A boundary line in reality does not exist.

Nevertheless, various methods, climatic, faunistic and geological, have been tried to secure a recognisable base. Deposits are related to the level of the present rivers and the establishment of the present régime.[90] Consideration is given to the morphological evolution of the valleys,[91] to the composition of the river-terraces, to prominent discontinuities,[92] and to the degree of deformation[93] and of weathering.[94] The base is put at the beginning of the uplift and rejuvenation, i.e. of the river-terraces and beaches which followed the Pliocene planation and crustal instability,[95] e.g. in California and eastern North America, at the drop in sea-level during the Sicilian stage,[96] or before the accordant series of marine sediments which culminated in the fluvio-lacustrine beds of Villafranche.[97]

It is drawn stratigraphically by most authorities, including the U.S. Geological Survey, at the bottom of the glacial deposits,[98] though arctic conditions may not have begun everywhere at the same time, as is believed, for example, by upholders of polar movements (see ch. LI) or by those, notably in France, who refer the first glaciation to the upper Pliocene[99] (see above) or who place glaciation in the latter half of the Pleistocene.[100] To make the Quaternary coincide with glaciation, the line is placed at the top of the Red Crag (see below), at the Amstelian,[101] at the end of the Mediterranean Pontic stage,[102] and in the Ponto-caspian region between the Apscheron and the Baku above[103] (see p. 1224). B. Eberl places it before his Donau glaciation.[104] The exact horizon, however, is difficult or impossible to determine.

The three critical areas for the study of this boundary in Europe are the Mediterranean (see p. 1255), East Anglia (see p. 696) and the Lower Rhine (see p. 1041) where the Amstelian, equated with Günz, contains a cold fauna and arctic polyzoa and foraminifera.[105] The transition is also found on Sylt[106] (Morsumkliff) where clays with *Hipparion gracile* are overlain by sands (Red Crag ?) containing pebbles of Scandinavian rocks, 1000 km distant from their source, and finally by true boulder-clay. This Crag of Sylt, which is also known from a number of borings on the mainland of Schleswig,[107] consists of Limonitic Sandstone (Pliocene) and of the Pleistocene estuarine Silts and Kaolinsand. Later mineral and pollen analyses place this sand in the Reuverian (Weyl *et al.*, 1955).

In the Mediterranean, where there is no direct connexion between the Villafranchian, Val d'Arno or other beds with the Günz glaciation of the Alps, the stratigraphical passage from older Pliocene into Calabrian suggests that the Pliocene should embrace the latter horizon. If, however, the evolving faunas dictate the boundary, the Calabrian should lie above and not below this line,[108] as was decided by the Vertebrate Section of the American Palaeontological Society in 1937[109] and by the 18th Geological Congress in 1948 (see below). The marine Calabrian (pre-Günz) is transgressive in Lombardy on lower Plaisancian and was preceded by an important mountain-building phase all over the Apennines and coincided with a pronounced cooling—the *immigrés du Nord* (see p. 1090) arrived at this time, namely, *Cyprina islandica*, *Corbula gibba* and 9% of the foraminifera. Moreover, the clays contain pollen of *Alnus*, *Pinus*, *Abies*, *Castanea*, Ericacaea and ferns, denoting a cold temperate climate.

In East Anglia, by referring the Cromerian to the Pliocene[110] and at the same

time to an interglacial epoch, as is commonly done (see p. 1015), the glacial beginnings are thrust into the earlier horizons. The base of the glacial succession is then placed at the bottom of the Butleyan,[111] Red Crag,[112] Norwich Crag,[113] Weybourne Crag,[114] Chillesford Clay[115] or Arctic Freshwater Bed.[116] The base of the Red Crag seems preferable since this coincides with an unconformity, with the first appearance of *Mammuthus meridionalis*, *Equus robustus* and *E. caballus*, and with the beginning of the climatic deterioration as shown by the mollusca and bryozoa. It accords with the current classification of the English Geological Survey (Chatwin, 1954).

In Holland, the boundary was placed at the bottom of the Icenian but is better placed at the base of the Amstelian[117] (Waltonian and Red Crag) which witnessed an increase of arctic species, e.g. *Elphidiella arctica* (see above), as is represented in the following table (for Sylt see above):

Stages	*England*	*Netherlands*	*Sylt*	*Alps*
Lower Pleistocene	Cromer Forest Bed Weybourne Crag, Chillesford Clay, Norwich Crag } Icenian Butleyan, Newbournian } Younger Red Crag Waltonian: Older Red Crag	Marine Icenian } Tiglian Amstelian (marine) Praetiglian (terrestr.) Poederlian Reuverian (terrestr.)	Kaolin-sand (fluviatile) Fine sand (estuarine)	Günz glaciation and Donau glaciation Calabrian Villafranch
Upper Pliocene	Boytonian, Gedgravian } Coralline Crag	Scaldisian	Limonite sandstone	Astian Plaisancian

In North America the critical areas are in the marine succession of southwest California (see p. 597), the terrestrial sequence of the San Pedro valley of Arizona (see p. 1091), and in the central United States. Here the Pleistocene deposits have been related to glaciation. Thus the Nebraskan drift in Iowa, Missouri and Illinois has incorporated quartzite gravels similar to those outside the glaciated area which are preglacial and appear to grade down the Mississippi valley into the Citronelle formation.[118] In the Great Plains, the Pliocene Ogallala Formation, a widespread sheet of terrestrial deposits sweeping upwards to the Rocky Mountains, is overlain by the Blancan—the beds are called Blanco in Texas,[119] Rexroad in Kansas[120] and Broadwater in Nebraska[121]—which is probably the equivalent of the Villafranchian of Europe and the Pinjor of India (see p. 1052). The short-jawed mastodont of the Villafranchian is related to the American *Stegomastodon* of the Blancan, and the European *Equus stenonis* to the American *Plesippus*.[122] *Castor* occurred in both. At the beginning of the Blancan there was a period of diastrophism and epeirogenetic uplift, a change in the molluscan faunas,[123] a major influx or expansion into North America from both Asia (see p. 1237) and South America (see p. 1238)—*Plesippus* (horse), *Borophagus* (dog) and *Procastoroides* (beaver) are diagnostic[124]—and a worsening of climate, for the fauna includes lemmings which are now restricted to boreal latitudes, and floating ice in streams from the Rocky Mountains carried striated erratics.[125]

The base is sought too on paleontological grounds, namely, in the last appearance of the mastodonts.[126] This line does not hold for North America where the mastodont continued into beds which are definitely Pleistocene or

even late-Pleistocene (see p. 865) and the line clashes with the division according to marine faunas and arbitrarily divides the Pliocene.[127] Since mammals are prone to linger beyond the period of their typical expression in geological time, e.g. *Hipparion* which persisted well into the Pleistocene in Algeria and with other forms into middle Pleistocene in East Africa (see p. 822), and the many glacial species which survived into "postglacial" time in North America (see p. 865), a line based upon the disappearance of forms is less satisfactory than one based upon the incursion of new species and genera, such as man,[128] or, following Haug's definition, of the new terrestrial mammals[129] *Elephas*, *Equus* and *Bos* (including *Bison* or *Leptobos*) which now appeared in Europe, south-west Asia, India, China and North America, possibly as a result of the climatic change which produced glaciation.[130] The Pleistocene then begins with the Villafranchian in Europe and with the Pinjor in India (see above).

This method has much to commend it, though it can be only rigidly applied in a single region. Even in Europe its value is relative and has its drawbacks[131]: it makes mastodont a Pleistocene animal and places the Villafranchian of Val d'Arno and Perrier in the Pleistocene when there was no indication of glaciation (though the *Sables de Chagny* in the Rhône valley are placed in the Günz glaciation[132] and the same Villafranchian fauna occurs in the Red and Norwich crags of East Anglia[133]) and, as in north China and north India, antedates the major diastrophisms which geologically should be the best boundary: in China, the great faunal change took place in the Hwangshui erosional phase between the Nihowan (Villafranchian) and Choukoutien (Cromerian) stages (see p. 545) and was associated with great epeirogenetic movements which elevated the lake-basins, formed deep gorges and created the modern Yellow River.[134] In India a very thick Siwalik Series, with a Villafranchian fauna and seemingly without any trace of glaciation, was intensely folded and peneplained before deposition again took place, so that the only "natural" boundary here is at the post-Villafranchian unconformity as Pilgrim has long contended (see p. 597). *Bos* and *Elephas* probably mark the end of the Pliocene in India though *Equus* may have appeared here for the first time in the Pleistocene since unlike the other genera it was immigrant into the country. In Africa, the fauna developed partly independently and also later.[135]

A widely accepted view, notably in France, closes the Pliocene with the Villafranchian fauna[136]—*Mammuthus meridionalis*, *Dicerorhinus etruscus*, *Equus stenonis*, *Trogontherium cuvieri*: the fauna is closer to other faunas whose Pliocene age is not in dispute and the Villafranchian is of the same age as the Calabrian which marks the end of a cycle of sedimentation. Gignoux[137] showed that the firstnamed animal arrived just before the end of the Astian in Tuscany and Piedmont, that the Villafranchian is the continental and freshwater facies of the Pliocene marine Calabrian[138] (as shown by the molluscan fauna and occurrence of *Mammuthus meridionalis*) and that *Mammuthus antiquus* belonged to the Pleistocene Sicilian. The Quaternary however more probably began with the Calabrian (see above). This was the decision of the International Geological Congress in London, 1948,[139] which preferred a boundary based on changes in marine faunas, the classical method of classifying rocks, particularly in Italy where terrestrial equivalents (Villafranchian) are also known and at the horizon where the climatic deterioration was first indicated. That the temperature of Europe was lowered at this

time is proved by the invasion of the Mediterranean basin by "cold" boreal mollusca and foraminifera, the plant remains at Lodi in the Plain of Lombardy and various places in the upper Val d'Arno, the diatoms of Haute-Loire and the solifluxion features in the outwash fans of Villafranchian age in the Dijon region.[140]

The Villafranchian horizon is known from north Africa,[141] where stones apparently worked by man have been reported,[142] and is seemingly coeval with the Kageran of east, central and south Africa (see p. 1126) which, besides its mammalian survivals from the Pliocene, contains true elephants.

In the Black Sea region, the boundary is perhaps to be drawn between the Kujalnik stage (Pliocene) and the Tschauda Beds (Pleistocene), and in the Caspian region between the Aktschagyl (Pliocene) and Apscheron (Pleistocene).[143]

In California, the only important faunistic break comes at the first appearance of a cold temperature towards the end of the Pliocene, i.e. the Santa Barbara Beds.[144]

Botanically, the boundary is drawn where such typical Tertiary plants as *Gingko*, *Taxodium* and *Magnolia* vanished from Europe,[145] or between the Reuverian and Tiglian.[146]

The discrepancy in time between the various lines is in practice neither serious nor troublesome. In its somewhat elastic connotation, and in its varied time of onset, the Pleistocene indeed resembles other geological periods. The bottom of the glacial deposits, if present, is as useful as any more scientific line: the difference in time between this and the other solutions is negligible by the geological clock.

Since lands and seas altered their outlines only to a minor degree during the Pleistocene[147] (see ch. XLIV), marine beds of this age, unlike those of earlier ages, are only exceptionally exposed on the present continents which they margin as raised beaches. To divide the Quaternary by its marine horizons, though occasionally advocated[148] and theoretically desirable, is scarcely feasible.

2. *Pleistocene Vulcanicity*

The Pleistocene was an Ice Age only in certain regions. Although these were vast and influenced others still vaster, a complete and perfectly proportioned history of the period should embrace a description of the forces that produced those lacustrine, fluviatile or aeolian accumulations which mantle the continents in lower latitudes and the marine sediments which floor the seas in all parts of the world. Subcrustal forces were also operative; signs of Pleistocene vulcanicity and earth-movements are visible in all parts of the world.

Europe. Vulcanicity in Europe was on a larger scale than now; many Tertiary igneous centres then became extinct. Numerous volcanoes were active in the Mediterranean region,[149] e.g. in Greece,[150] the Aegean Sea[151] (Santorin) and in the Alban Hills and Phlegrean Fields.[152] Here the first eruptions were of Chellean and the last volcanic manifestations in Latium of Mousterian age (upper palaeolithic man dug shelters in the volcanic tuffs). Vesuvius[153] and Etna[154] both began in the Pleistocene. Volcanic products of this time have also been discovered in deposits in Rome.[155] Scoriaceous cones and lavas occurred in Sardinia[156] and eruptions in Catalonia.[157] Lapilli

are associated with *Mammuthus meridionalis* and *Hippopotamus* south-east of Cuidad Real and lavas with beds containing *Mammuthus primigenius* near Gerona.[158] North Africa also had volcanic activity[159] (see below).

There were eruptions too in the Central Plateau of France[160] (e.g. in the region of the Puys, on the east slope of Mont Dore and in Haut-Vivarais), the Silesian Sudetes,[161] in Moravia, at Kammerbühl and Eisenbühl in north Bohemia[162] (with thermal springs), and in Rumania[163] (Banat). The powerful basalt volcanoes of the Laacher See district of the Eifel,[164] the accompaniments of displacements along the Rhine,[165] including the Neuwied basin, were active during the Riss-Würm interglacial and the younger loess period, though their outbreak, with its phonolytic tuffs and pumice, continued to the end of the Lower or Insel terrace[166] (see p. 1043) or into upper Magdalenian or even, from the evidence of fir and beech, into Ancylus,[167] early Littorina[168] or Alleröd time.[169] The "postglacial" volcano of Köfel in Oetztal,[170] which was erupting in the interval between Gschnitz I and II[171] or in Alleröd time,[172] is the sole representative of Alpine Quaternary vulcanicity: it has, however, been interpreted as the crater of a gigantic meteor.[173]

Glacial and vulcanoglacial formations of Pleistocene age are interbedded in Iceland[174] which had a Pleistocene thermal activity[175]—volcanic ashes from Iceland were carried to south-west Norway in Alleröd time (see p. 1435). Quaternary volcanic products are also known from Spitsbergen.[176] Beerenberg (2341 m) in Jan Mayen is a product of this time (see p. 725). By contrast, the sediments on the sea-floor prove that the volcanic activity in the Cape Verde Islands was on a smaller scale.[177] The Canary Islands had a Pleistocene vulcanicity[178] which included basalts, trachytes and phonolites.

Asia. The Pleistocene witnessed sporadic vulcanicity in Asia and the extinction of the volcanoes of Ararat, Sahend, Gawalee and Demawend.[179] There were trachytic and andesitic volcanoes in Asia Minor[180] and along the faults of Armenia.[181] Ashes have been found near the boundary of the Mindel and Riss fluvioglacial deposits in the Don valley[182] and in the Perekop Isthmus.[183] With similar materials they were ejected in the Caucasus,[184] while basalts were poured out in Iraq,[185] north Palestine,[186] Transjordania,[187] Arabia,[188] and in the regions of the Dead Sea and Galilee.[189]

Basalt lavas were extruded in north Siberia,[190] along the Siberian–Mongolian frontier,[191] in Mongolia,[192] Manchuria[193] and Korea,[194] and contemporaneous vulcanism has been detected in China[195] and Kuen-lun.[196] Andesites, dacites and liparites were erupted in Kamchatka and around the Sea of Okhotsk[197] and volcanoes were active in Japan,[198] the Kuriles,[199] and in other Pacific islands.[200] Tuffs and lavas were emitted in the Dutch East Indies[201]—Java had then its first major phase of eruptions and Sumatra most of its volcanoes. The main mass of the present active volcanoes of the Malayan arc was built up in the Quaternary.[202] The Hawaiian Islands had their Pleistocene vulcanicity.[203]

America. Volcanic action of this period has been established for North America[204] from Alaska to the Sierra Nevadas, and for the West Indies,[205] central America[206] (New Mexico, Guatemala, Columbia), and the whole length of the Andes.[207] Tremendous activity characterised western central America, and south Mexico was studded with volcanoes. Popocatepetl's lack of Pleistocene glaciers (cf. p. 732) has been attributed to later volcanic activity which raised its height.[208]

Africa and Australasia. The serious faulting along the Rift Valley of East Africa (see below) was accompanied or followed about the middle of the Pleistocene (Interpluvial) by powerful volcanic outbursts[209] (basalts, trachytes, rhyolites, tuffs) which extended, in association with the east and west rift-valleys, for more than 900 miles (*c.* 1400 km), from Abyssinia to the Giant Craterland of Tanganyika. They built up the volcanic mountains of Emi Kusi, Eberu, Kulal, Longonot, Marsabit, Rungwe, Seeswa, etc., and made such gigantic caldera as Menengai: the ashes and tuffs built immensely thick deposits over the area of the rifts, and often contributed largely to the lake-deposits, affecting vegetation, rainfall run-off, depth of ground-water and the whole hydrological cycle. A volcanic phase occurred in Morocco, Algeria and Tunisia, in the Cameroons and near Pretoria in South Africa.[210] Lavas were poured out in Madagascar,[211] New Guinea[212] and the North Island of New Zealand,[213] while contemporary igneous rocks (basalts, trachyandesites, limburgites, scoria-cones, ash beds) are recorded from South Australia, western Victoria and northern Queensland,[214] and from Antarctica, as about Ross Sea,[215] in Deception Island[216] and on Kerguelen.[217]

3. *Pleistocene Terrestrial Movements*

The horizontality of the Mediterranean beaches (see p. 1255), the North Atlantic strandflat (see p. 1250), the British infraglacial beach (see p. 1257) and the terraces of eastern North America (see p. 1259) proves that no serious movements disturbed the North Atlantic region during Quaternary time, though they did so in volcanic Iceland[218] (where glacial and postglacial dislocations have considerably influenced the topography) and along the rest of the Dolphin Rise which may owe much of its high relief to diastrophic and volcanic movements of late-Tertiary and Pleistocene age,[219] and may, it has been suggested,[220] have persisted as a land ridge into Mindel-Riss time.

Elsewhere this state of affairs was far from being the case and the normal processes of diastrophism, the aftermath of those of Tertiary age, were by no means in abeyance. The Pleistocene indeed witnessed earth-movements on a considerable, even catastrophic scale.[221] There is evidence that it created mountains and ocean deeps of a size previously unequalled[222]—a post-Tertiary age has been proved for at least one deep-sea trench, its movements being greater than for any other corresponding period of geological time. The Pleistocene indeed represents one of the crescendi in the earth's tectonic history: it has raised high the rate of total denudation, for the present mean may be twice that of the Cainozoic and fifteen times that of all geological time since the opening of the Palaeozoic era.[223] The movements included the epistrophic movements (see ch. XLV) which affected *c.* 40 million sq. km of the continents and 330 million sq. km of the ocean floor, i.e. 70% of the total surface of the earth[224]: they have been termed the "pasadeniar movement" (see p. 606) or the "Mogian revolution".[225]

Faulting, uplift and crustal warping have been proved for almost all quarters of the globe. Faults, with throws of up to 100 m or more, have been observed in many countries[226] traversing glaciated rock-surfaces,[227] drifts,[228] till,[229] moraines,[230] outwash fans,[231] loess,[232] varve clays,[233] strand-lines and lake-terraces, e.g. in the Great Basin and Colorado Basin of North America,[234] Fennoscandia[235] and in the East African rift-valleys.[236] They may have raised the "erratic height" on the slope of the Eulengebirge by

more than 100 m[237] and have brought the Balkans and other areas above the snowline during the last glaciation (see p. 653).

Eurafrica. The Abyssinian plateau was tilted to the north-east[238] and the faulted massifs of the French Sahara and Sudan were then largely elevated.[239] Pleistocene rifting, accompanied by gentle warping, took place in Africa along troughs of ancient origin.[240] The development of the Western Rift, with its contemporaneous longitudinal bulges, modified the peneplain of central Africa which extended into Uganda and the head waters of the Congo system. It isolated this region and created Lake Victoria which shares Nilotic affinities with Lakes Edward and Kivu.[241] The movements also spread into south-west Africa.[242]

Faults of this age pronouncedly disturbed the Boden See area of Switzerland (see p. 265), parts of the southern Alps, the Vienna basin,[243] the Sea of Marmora[244] and the Aegean (see p. 1220). Epeirogenetic movements and warpings affected the south Carpathians and the Dinaric peneplain and extended into Istria[245] and the Balkans.[246] They were significant in Pleistocene Holland and Germany[247] (see p. 1265), where thrusting raised the salt domes of Lüneburg, Sperenberg and other places.[248] They caused river-captures in the Ardennes,[249] folded the older beds in south Italy,[250] domed up Greece south of the Gulf of Corinth[251] (see p. 1263) and pressed up folds in Tunisia[252] (with faults), Algeria,[253] Morocco[254] and the Iberian Peninsula.[255] Structural deformation was taking place in the Alps (see p. 1326), where it was largely interglacial (Mindel-Riss[256]), and in Niedere Tauern.[257] In Russia[258] the forces raised the Ural Mountains, Transvolga region, Podolian plateau, Caucasus and Russian platform, the Asov-Podolsky horst and the Crimea (the uplift was 400–500 m) and depressed other structural elements, including the Pinsk Marshes, the Dnieper and Don basins, the middle Volga, the Caspian region and Petschoraland—this orogenic phase, of Mindel-Riss age, was termed Baku ("Bakinsk") by G. Mirčink.[259] In the Caucasus, it is suggested, the glaciations were genetically related to them.[260] Fault displacements in the Rhine Rift Valley,[261] continuing those of Tertiary time, were of the order of 887 m: movements are still taking place.[262]

Asia. Asia was likewise subject to powerful and far-reaching disturbances. A structural break, of middle Pleistocene age, produced an angular unconformity from the Caucasus to central and eastern Asia.[263] The fault troughs of the Dead Sea, Red Sea, Jordan Valley, Gulf of Aden, Persian Gulf and Arabian Sea then received their present form.[264] Faults, mainly of interpluvial or middle Pleistocene age, tilted the strandlines of the Pluvial lake in the Jordan Valley (see p. 1118) and contributed to its sinking.[265] Syria and Arabia were raised and tilted and subject to large scale folding[266]—marine Pleistocene occurs up to 350 m in south Syria—and Mysis Olympus was raised *c.* 1000 m.[267] Uplift and warping affected the Tertiary peneplain in central Turkestan, elevating the crest-line of Tienshan[268] and depressing the basins by possibly 3000 m.[269] Earth-movements elevated the Caucasus[270]—the amount since Mindel time is estimated at 1200 m and since Riss time at 400 m—and disturbed coastal Burma and the major formation boundaries when the entire land mass of that country with the Shan Highlands was uplifted.[271] They raised the Lake Baikal region[272]—Lake Baikal was deepened—central Asia[273] (by 2000 m) and north Manchuria[274]; warped

Peninsular India[275] and altered the configuration of several of the river-systems; and imparted a broad uplift to the Sub-Himalayas in north-west India, raised the Pir Panjal range by 1800–2400 m, and deformed the country along the structural trend of the Siwalik folding.[276] The Himalayas[277] were also increased in height by possibly 2000 m and their folded belt was widened towards the peninsula. These extremely youthful orogenic movements in the Himalayas produced upwarps continuing the rising anticlines of the Tertiary, and in the Indo-Gangetic trough covered the earlier beds with a great thickness of Pleistocene sediments,[278] including coarse conglomerates. They reversed the drainage of north India[279] and dismembered the hypothetical Indobrahm of E. H. Pascoe (Pilgrim's Siwalik River) which had its source somewhere in Upper Assam or China and flowed westwards along the courses of the present middle Brahmaputra, the Ganges and the Indus, to discharge into the receding Sind Gulf of the Arabian Sea. They lifted the plant zones so that in Minya Gongkar in Tibet, tropical plants were transferred to the nival zone[280]; drove the monsoon forest southwards; compelled the Pleistocene ice of Tienshan to retire[281]; and increased the desiccation of central Asia.[282] Here, continued uplift is seen in the gorges of the Oxus, Indus, Brahmaputra and Yangtze-kiang which flow from it. The uplift since the Glacial period has been 500–1000 m, i.e. 2·5–5 m per century.[283]

An orographic revival affected Minya Gongkar[284] and Shansi and Shensi[285] and through an uplift estimated at 3400 m initiated the Fen-ho physiographic stage in north China[286] which preceded the Sanmenian phase of sedimentation and separated these Pleistocene beds from the earlier (Pliocene) Nihowan deposits. Weighting of the Hwang-ho plain by sediments caused a downwarping of the borders of the Shantung block by as much as 1000–1500 m,[287] at least part of this of Pleistocene age, and was accompanied by orogeny in Mongolia and Western Hopei.

A sharp continental uplift, more clearly defined than that at the top of the Pliocene, took place in the Sanmenian or middle Pleistocene period in China[288] (Hwangshui period), as it did in Burma[289] and north-west India.[290] In China rivers cut gorges and caves, the modern Hwang-ho and Yangtze-kiang drainages came into being, lake-basins were drained and uplifted, and extensive fans of red clays and conglomerates bordered the basins ("Age of Conglomerates and Terraces")—these "boulder-conglomerates" accumulated from Shansi to Yunnan, from Mongolian Altai to Tienshan and north India, e.g. Kashmir and Punjab, and in Burma, and fissures were formed in limestones,[291] e.g. in south Tsinling, Indo-China, Burma and Java. The Khingan Range, the ranges of Tsinling and the plateaux of Shansi and Mongolia were uplifted and the intermontane basins of Ordos, Fen-ho, Yushê and of the Peking plain sank. A later, Chengshui erosion interval[292] preceded the loess and interrupted the laterite formation in south China. The whole China coast from Korea to Kwangtung has sunk so that raised beaches are entirely missing.[293]

Russian geologists believe that faults of this age determine the outlines of Severnaya Zemlya[294] and fashioned the Siberian shore of the Arctic Ocean, a concept supported by Quaternary rifts in all parts of Siberia and a postulated glaciation of north Siberia from a land-mass north of the present coast.[295] The movements extended as far as Kamchatka.[296]

America. Paroxysms, accompanied by extensive block-faulting, dismembered and elevated the central American-Antillean lands, completing the

foundering of the Antillean Sea and overdeepening the Gulf of Mexico and Caribbean Sea[297]: marine Pleistocene invertebrate faunas have been carried down to a depth of more than 1000 m in southern Louisiana[298] and the base of the Tertiary near New Orleans has been dropped to over 10,000 m.[299] The movements strongly upheaved and faulted the Barbados,[300] carried coral reefs to 445 m in mobile Haiti,[301] raised marine beds in the Lesser Antilles to 275 m[302] and in Cuba to 297 m[303] and deformed the West Indies.[304]

The Appalachians were brought to their existing altitudes during the Quaternary.[305] Uplifts of a few thousands of metres characterised the whole of western North America[306] which, as in California, saw the severest diastrophism since the late Jurassic and experienced its greatest thrusting and faulting.[307] The movements arched up the whole of the Great Plains and led to the relative abundance of keystone fault-blocks in the Great Basin and western Montana, thereby initiating a notable cycle of canyon cutting (Thom, 1955); they broke up, for example, Nevada and south-east California; formed the Californian Coast Ranges as we know them to-day; and revived such ranges as the Wasatch, the Ruby Mountains and many others,[308] making among other features the trough which was later to become the Bay of San Francisco. This period has been named the Ozarkian,[309] Sierran[310] or Pasadenian[311]: it produced a strong unconformity of mid-Pleistocene date. Similar deformation, which ranged up to 2700 m and widely rejuvenated the valleys and was pronounced in mid-Pleistocene times, has been proved by biotic and physiographic means for the whole of the Andes[312] whose elevation has separated the bird life into cis- and trans-Andean areas[313] and, as in South Africa[314] and central Asia (see above), has increased the desiccation.[315] Faulting may have emphasised the offlying ocean deeps.[316]

Pacific. Disturbances were also distributed throughout the rest of the mobile belt around the Pacific, as in the Philippine Islands[317] and New Caledonia,[318] while extensive readjustments were made along the arc of the Malayan archipelago and in the East Indies,[319] including Java where an upward crustal movement, connected with volcanic activity, folded and warped the inland basins. Earth-movements considerably affected the unstable area of Wallacea between the Sunda and Sahul shelves.[320] Discontinuous uplifts and block-faulting took place in the Banda arcs[321] and in Timor[322] (see below). Crustal warping and block-faulting with tilting were active in New Zealand[323] ("Kaikoura orogeny"), and there were vertical displacements of considerable size (*c.* 600 m) in Papua.[324] Coral reefs were raised 300 m in the Solomon Islands[325] and to 1000 m in Celebes.[326]

A broad regional uplift of up to 1800 m, accompanied by widespread normal faulting, occurred in the Kosciusko Mountains, New South Wales[327] ("Kosciusko" or "plateau" period[328]), and as a broad geanticline parallel to the coast spread through the south of the continent,[329] thereby originating the internal drainage system of the Great Artesian Basin. The rift-valleys of South Australia owe their form to complementary downward movements of this age,[330] and the faults bounding the east coast of Australia also moved, dropping down the platform on which the Great Barrier Reef was built.[331] The north-west coast of Australia has been tilted and faulted so that the continental shelf is marked by the 300 fathom (*c.* 550 m) line.[332] Coral terraces of the same date have been raised 1300 m in Timor and 1000–1700 m in New

Guinea where the central ranges were elevated as a vast concourse of earth blocks.[333] Macquarie Island is a residual horst left by profound postglacial block-faulting (see p. 735).

These movements are probably continuations of those of Tertiary times: they have been regarded as differential,[334] as due to variations in intensity,[335] or as continuous movements modified by the Pleistocene climatic rhythm.[336]

The Pleistocene in its earlier portion was affected by orogenesis in different parts of the globe, e.g. the outer zones of the eastern Andes, in western North America, in the southern marginal zone of the Himalayas and in the lower Rhine basin (Stille, 1955). Yet the most important phase was seemingly the great interglacial ("bakinsk" of G. Mirčink,[337] the "Ortenau" phase of O. Wittmann[338]).

The Pleistocene high continents, restricted epicontinental seas, notable folding and seismic activity, and diversified climates suggest the twilight between two geological periods.[339]

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CHAPTER XXX

DRIFT-ICE VERSUS LAND-ICE

1. *Débâcles*

The glacial field offered boundless opportunities for indulgence in the wildest of conjectures and the boldest of speculations: many of these exceeded the bounds of the absurd. The origin of granite and basalt, whether aqueous or igneous, was not more strenuously debated than were the nature and duration of the processes which accumulated the *Diluvium*. Every step forward was fiercely contested. The dust and din of the contending schools have died down so that this branch of geological enquiry has like others passed into a period of orderly progress. Yet the glacialist still finds much to baffle him.

Although the clays, sands and gravels belong to the youngest and most accessible formation, their apparently chaotic state and seeming lack of interest made them the last to be investigated; they were for long a synonym for confusion, and except for their fossil shells and bones seemed unattractive and unimportant. The "extraneous rubbish" was a troublesome hindrance in examining the "solid" geology. Long after Agassiz had revived the glacial theory, official state surveys ignored them. Thus the British drifts were passed over almost without scrutiny until most of southern England had been examined. They were first mapped in Norfolk by J. Trimmer.[1] Their mapping was only undertaken when, somewhat belatedly, their connexion with agriculture, drainage, dwelling sites and engineering problems had become recognised.

The subject has a history extending over more than a century. Reviews[2] and systematic treatises by Agassiz[3] (1840, 1847), Mousson[4] (1854), Heim[5] (1885), Falsan[6] (1889), Hess[7] (1904), Woldstedt[8] (1929, 1954) and R. v. Klebelsberg[9] (1948/49) on the continent of Europe, by A. Geikie[10] (1863), J. Geikie[11] (1874, 1878, 1894, 1914) and W. B. Wright[12] (1914, 1937) in Britain, and by G. F. Wright[13] (1889, 1911, 1920), A. P. Coleman[14] (1926, 1941) and R. F. Flint[15] (1947) in North America have dealt comprehensively with the state of knowledge of certain parts of it at the time of their publication. Together, they record the advance of glacial observation and thought during the last hundred years.

Penck and Brückner's *Die Alpen im Eiszeitalter* (1909) co-ordinated a mass of data dealing with the Alps and provided a basis for glacial nomenclature and chronology that has had world-wide reactions.

Early views on erratics. Erratics or "foundlings" (Ger. *Findlinge*; Ital. *trovanti*) early attracted the attention of naturalists; this was due to their conspicuousness where they bestrewed the plains or rested upon mountain flanks, and to their contrast in colour and texture with the underlying rocks and soils. They were scattered by Nature in her anger. Aeschylus and Strabo regarded them as remains of a hail of pebbles hurled by Hercules and Jupiter, and later writers derived them from planets or comets or placed

them in a sort of special mythology as "giants' putting stones", "devil's burdens" and "witches hearth stones" brought by Samson or Goliath or by giants, dwarfs, the devil, Thor, Odin or Robin Hood (see p. 362). Even as late as 1875 they were regarded as the products *in situ* of marine precipitation.[16]

Those on the eastern flanks of the Jura Mountains were especially remarkable, exciting more interest than any in the Alps; here the chaos from avalanches, mountain torrents and glaciers made them less noticeable except at Monthey[17] in Valais where granites from Mont Blanc are 27 miles (*c.* 43 km) from their source. The *Pierre des Marmettes* at this place contains over 60,000 cu. ft (2027 cu. m) of rock[18] and the *Pierre à bot* near Neuchâtel at 670 m measures 19 m by 15 m by 12 m (see p. 363). On the Jura slopes, the erratics reach their highest altitude opposite the great Alpine valleys, especially the Rhône, as von Buch[19] and de Saussure[20] observed (actually at the south end of Lac de Neuchâtel[21]).

S. G. Gruner[22] noticed that the blocks came from the Alps. Von Buch placed this beyond doubt by tracing them to their source in Mont Blanc and Valais and supplementing the observations of de Saussure, D. Dolomieu, C. Escher and G. Studer. He showed too that the dispersal was not restricted to the valleys opening on to the Swiss Plain but was radial from the Alps and that the erratics of north-west Europe, though more distant from their source and scattered on a vaster scale, resembled those of Switzerland in their mode of occurrence. W. Schultz[23] gathered further details of their distribution and F. Hoffmann[24] tracked them through Westphalia and Saxony and G. G. Pusch[25] followed them through Poland and Russia. While some writers thought they were local,[26] i.e. from mountains or rocks that had been subsequently destroyed, or from the south[27] (a derivation recently affirmed[28]), C. F. v. Ahrenswald[29] noticed as early as 1775 the similarity of the Trilobita and Orthoceridae in boulders of the Pomeranian and Mecklenburg drifts to those *in situ* in Gotland. Von Buch,[30] indeed, demonstrated conclusively that they came from the north, mainly from Scandinavia. He followed their southern limit across Germany (as Murchison[31] afterwards did for Russia, where he found they spread farthest down the Dnieper and Don) and noted that they became smaller southwards. J. Durocher[32] found a like diminution in the Finnish erratics over Russia and Poland and remarked that while the erratics in these countries hailed from Finland, south of Berlin they came mostly from Sweden and in Denmark from Norway. This conclusion agreed generally with observations by Pusch and J. F. L. Hausmann[33] in the Netherlands. These directions were seen to conform with Sefström's "diluvial scratches"[34] which, as T. Bergmann (1775–8), C. de Lasteyrie and P. A. Siljeström observed[35] (they escaped von Buch's notice), ran north–south in Sweden and west–east in Finland and north Russia and parallel with the surface-features.[36] L. Vanuxem[37] and J. Hall[38] discovered a like southerly carry in North America, that the crystalline rocks had travelled farthest and that the distribution had a southern limit.

The striae found many conflicting explanations. They were regarded as the outcrops of slaty cleavage or crystalline structure,[39] and even after the glacial theory was enunciated were attributed to the settling of boulder-clay following infiltration[40] and to structural phenomena,[41] landslips,[42] cart wheels or hob-nailed boots![43] Roches moutonnées fared little better: exfoliation and ordinary atmospheric weathering fashioned them.[44]

Erratics naturally incited the study of the disarray of clays, sands and

gravels that constitute the drift, though many regarded their origin as distinct and the problem they presented as less serious. No force then known, it was agreed, could have transported erratics over great distances and across the Baltic basin in north Europe's dispersal region or over the Swiss Plain in the case of the Alpine radiation.

Catastrophic phase. In the infancy of geology, before the enunciation of Lyell's Doctrine of Uniformity and K. E. A. v. Hoff's *Aktualismus*,[45] the drift and its associated phenomena were the subject of crude, extravagant hypotheses (glacier-tables, for example, spouted from glaciers like mushrooms on their stalks), of fanciful speculations, and of hasty deductions, products of unbridled imagination rather than of scientific enquiry. Chaotic turmoil and catastrophes, generated by causes often more difficult to understand than the phenomena themselves, separated man from the Tertiary era.

Mighty convulsions due to approaching comets[46] or disrupting heavenly bodies[47]; a halt or change in the earth's revolution about its axis[48]; extensive collapse of mountains[49] or of the roofs of vast subterranean caverns which expelled their expansive fluid or gases with explosive impetuosity[50]; the paroxysmic erection of the Alps[51]—all were seriously invoked. Subterranean volcanic outbursts were also responsible[52] (erratics were bombs,[53] block-moraines crater rims[54]). Eruptions and earthquakes operated in North America[55] and even Lyell[56] thought earthquakes might explain some of the Alpine erratics.

In less violent form, the Swiss erratics were transported by drift-wood (hence the bituminous wood in many Swiss localities) or were ferried in glacier-lakes[57] or in a single sheet of water which submerged the Swiss Plain and penetrated the Alpine valleys.[58] Alternatively, they glided over an inclined plane, afterwards carved into the present relief, which sloped continuously from the Alpine summits to the Juras.[59] This reconstruction was obviously incompatible with the dimensions of the erratics[60] (the gradient would be only 1° 8′ 50″[61] if they had been carried no farther than the Swiss frontier), the lack of signs of attrition, their occurrence in a zone instead of at a definite height, and, as was early shown,[62] their dispersal after the valleys had been excavated.

Diluvial hypothesis. A natural impulse was to ascribe the whole of the seemingly tumultuous and disorderly deposits to the passage of a vast flood. The Deluge or *Sintflut* (general flood), the last of the catastrophes, was long and widely accepted as the cause of glacial phenomena. Its "resistless, world-wide currents", de Saussure's *violente et grande débâcle*,[63] were postulated not as part of a cosmogony but as a legitimate attempt to solve a specific problem, though the freshness and apparent recency of the phenomena were welcomed as proof of Biblical records and of the floods of many scattered traditions—a relic of the hypothesis survives in the name *Diluvium* still used in German-speaking countries for the Pleistocene period.

W. Smith was among the first to separate the "superficial deposits" from the "regular strata", referring them to a different and more tumultuous origin. Those of the Deluge, Werner's *aufgeschwemmtes Gebirge*, were distinguished from the *Alluvium*, which proceeded from causes still operating as R. Bald,[64] who spoke of "old" and "recent" alluvial covers, maintained for Scotland and W. Buckland[65] for England. Buckland and G. A. Mantell[66] designated them *Diluvium* and *Alluvium*, a distinction generally admitted after

Cuvier[67] published his work on fossil animals. The separation was based on the invariable succession of the *Diluvium* by the *Alluvium*, on the difference in the organic remains, including the absence of traces of man from the older deposits, and on the *Alluvium's* tranquil formation.

This Deluge swept over the earth in incalculable volume, generally from north to south (hence Murchison's term Northern Drift[68]), though in Switzerland it came from the south-east out of the Alpine valleys[69] (see above). Extravagant effects were attributed to it. As it rushed through the great valleys, e.g. the Ancient Straits of Malvern,[70] it sculptured and transformed the terrestrial features. It inscribed the striations,[71] rounded the contours,[72] disintegrated the rocks,[73] scooped out hollows on the impact side of obstacles,[74] eroded glacial spillways[75] and giant kettles (like the kettle afterwards found on the Hinterstock[76] at 1730 m or 300 m above the floor of the Aare valley or that at *c.* 900 m on Dovrefjeld[77]), excavated valleys[78] and lake-basins including the Great Lakes,[79] severed England from the continent (H. H. Howorth), moulded drumlins by its undertow,[80] and bestrewed half a world with its wreckage.

Crags, knolls and mounds, confusedly hurled,
The fragments of an ancient world.

To the wreckage belong the erratics (sometimes seen to be striated[81]) and the drift named "cataclysmal Diluvium", *Terrain diluvien cataclystique*,[82] *Terrain Clysmien ou Diluvien*[83]—others preferred neutral terms[84] like *terrain erratique, nappes erratiques* or Erratic Tertiaries. In France the flood deposited the *limon des plateaux* and in England produced washed-in cave deposits, stanniferous gravels in Cornwall,[85] flint gravels and plateau drift in the south,[86] and as elsewhere, shelly gravels, water-laid and water-worn material and boulders in the terraces. Catastrophic floods from the north carried an immense quantity of mud, turf, water plants and other organic matter, depositing it in a finely divided state as the Russian blackearth.[87] They were responsible for the chaotic appearance of some of the deposits, as those of Lago di Garda to which Dante referred in his *Inferno*.

The effects upon life were far-reaching. The Deluge broke the bones of vertebrates caught up in it[88]; transported arctic plants into lower latitudes[89]; and scattered the pre-diluvial vegetation as "Noah's woods" (submerged forests). It mingled land and aquatic animals[90] and northern and southern species, drifting them into caves[91] (as believed, for example, by J. F. Esper and G. A. Goldfuss), and wiped out much of the antediluvial fauna[92] (G. Wahlenberg's *preadamitiska organiska bildningar*[93]), including the Siberian mammoth which by a "miracle of Providence" survived through two epochs[94] (*Dicyclotherium* of G. St. Hilaire[95]). It necessitated a new, postdiluvial creation[96] since the bones, previously thought to belong to griffins, dragons or a giant race of men,[97] to the dead animals of former menageries or as in Tuscany to Hannibal's war-elephants,[98] were shown by Cuvier[99] to be elephants and rhinoceroses specifically distinct from living species.

Notwithstanding Playfair's protests (see p. 624), the hypothesis found wide support in north-west Europe.[100] Sefström[101] imagined *Den Petridelauniska Floden* or *Rullstenflod* ("flood of rolled stones") had overwhelmed all Scandinavia from north to south, deviating locally with the relief, as W. Böthingk[102] pointed out. It accorded with the striae, as on the flanks of Snehaetten at 1234 m (P. A. Siljeström) and near Hardanger at 1800 m (B. M. Keilhau). In

agreement also were the roches moutonnées, whose northern sides were rounded and southern sides rough,[103] the alignment of the osar,[104] and the movement of the few erratics then traced.

The diluvial hypothesis had many adherents in Britain[105] and was strongly and repeatedly championed by Buckland[106] who postulated a universal flood which submerged the highest summits. He sought its source in the north, notwithstanding the warm character of its fauna, including the hippopotamus, which had led others to believe in both a southern and a northern flood.[107] The hypothesis reigned undisputed in North America until 1841[108] and was firmly held in Switzerland[109] where the cataclysmically retreating waters scoured out the basins of the Swiss lakes.[110] While the middle of the 19th century saw its general abandonment, some geologists, e.g. A. Sedgwick and J. Phillips in Britain, remained staunch and later supporters have not been lacking[111]; H. H. Howorth[112] in particular defended the diluvial creed.

The causes of the sudden and violent floods that swept over the face of the earth, with depths of up to 5000 ft[113] (1520 m) and a velocity computed at 19,460 ft (5930 m) per second,[114] were mostly obscure and fantastic, involving agencies outside the realm of human knowledge and observation. They were given, as Playfair[115] said, with a want of precision and with much reserve and mystery, for whence or whither were questions difficult to answer.

The waters were condensed out of a primordial atmosphere[116] or descended from the nebulous trains of comets entangled in the earth's atmosphere.[117] They spouted from subterranean caverns[118] and accompanied the convulsions that suddenly upheaved the mountains of the world,[119] including Scandinavia, the Alps and Carpathians, or that elevated hypothetical continents[120] or the ocean floor.[121] They also sprang from the bursting of extensive lakes[122] over the Swiss Plain or the plains of north-west Europe, from the emptying of glacier-lakes,[123] or from the sudden melting of snows.[124] This "erratic thaw"[125] was induced by a sudden lowering of the Alps[126] or by gases escaping from igneous matter[127] in the Alps, Pyrenees or south Italy. Alternatively, the waters came from the polar ice,[128] melted by a shift of the earth's axis.[129]

The culminating expression of these paroxysmal dynamics was the "wave of translation" enunciated by Hall[130] and elaborated by several Cambridge mathematicians.[131] This attempt to put the diluvial hypothesis on a systematic basis postulated a terrestrial upheaval by successive and powerful starts, the percussions raising gigantic waves in the oceans. Although the waves had no rational explanation, they continued to be accepted by a number of British and American geologists[132] for over 30 years in the original or some modified form. Forchhammer[133] also attributed the *Rullstensformationen* to a wave-like rise and fall of the surface associated with plutonic activity.

Objections to the floods were stated by numerous writers but no more convincingly than by Charpentier[134] and Agassiz.[135] Thus the till lacks stratification and any separation according to weight or volume; the erratics have sharp edges and angles; some of the blocks are unstable; lakes have been preserved (a difficulty Playfair and K. Schimper emphasised); and no current could be charged to a depth of *c.* 750 m.

Yet many facts suggested a submergence. To these belonged the marine shells in the drifts (see p. 630) including the Yoldia, Clyde and Champlain

clays whose correct position was not appreciated until much later (see ch. XLV); rock-surfaces perforated by Pholades[136]; giant-kettles[137]; sodium chloride in Belgian loess[138]; relict faunas in Swedish and other lakes[139] (see ch. XLVIII); halophyte plants in north Germany (the maritime plants are really related to the lateglacial submergence, the halophytes to salt springs from the Zechstein[140]); and the maritime plants around the Great Lakes[141] (first interpreted in this way by J. Torrey[142] in 1843) and other inland waters, e.g. in Sweden[143] (Vättern and Vänern) and Scotland[144]—the so-called maritime plants round the Great Lakes include representatives of various types and may be connected merely with suitable habitats,[145] e.g. warm sandy soils or salt springs, with the Laurentian glacier-lakes,[146] or may have descended from the Appalachian upland,[147] in either case being unrelated to a lateglacial submergence. Moreover, raised sea-margins occurred in Scandinavia, Britain and North America—shelves of varied origin, such as weather, river, lake or plough terraces, were cited as evidence[148]; erratics were mingled and intercrossed[149] and widely distributed from small outcrops[150]; and much of the drift, with its lamination and alternating fine and coarse layers, was obviously water-worn and water-laid.

2. *Drift Theory*

The conflict with Huttonian principles involved in conveying huge erratics by marine currents for scores or hundreds of miles led to the calling in of floating ice. In its new guise, the diluvial hypothesis was no longer discordant with the doctrine of uniformity since duration and not intensity was important: Pleistocene events were removed from the catastrophes. It was imagined, in accord with the fresh discoveries of such polar explorers as W. E. Parry, W Scorseby, J. Franklin and E. K. Kane, that local glaciers on the higher mountains released ice-rafts and bergs, occasionally coast-ice[151] or ice-foot,[152] which sailed out over the submerged lands in a polar or "palaeocrystic sea" (see p. 191). The drift-ice of this Great Submergence swept over west Scotland and the Outer Hebrides from the north-west in a sea 3000 ft (*c.* 900 m) deep.[153] It grated on the sides and floors of the valleys and striated them; produced cross striae[154] and terminal curvature, as Darwin stated for Moel Tryfaen,[155] and rotating, ground out rock-basins.[156] At the final melting, the load was dropped as erratics and drift, far removed in places from their source and distributed according to the interplay of contending currents and tides, the weight of the debris, and the quantity and draught of the ice.

The glacial currents compelled all animals, including northern ones, to migrate southwards.[157] They gouged out hollows in the drifts,[158] eroded the Swiss and Great Lakes[159] and the basin of the North Sea,[160] deposited the "head" of southern England,[161] and washed the boulder-clay, leaving behind the "middle glacial" sands and gravels.[162] North Germany had a coastal facies[163] and kettle-holes marked the shores of the ice-laden sea.[164]

That the waters were cold was demonstrated by the arctic life in the Clyde clays,[165] in the "ice-sea" (*isshav*) of the Baltic[166] (see p. 1295) and in the Mediterranean Sicilian.[167] Reindeer and arctic birds in south France[168] and arctic plants in Devonshire and Scania (see p. 1066), bore witness to the climatic severity of the adjacent lands.

This glacio-natant hypothesis, though earlier anticipated,[169] is usually

associated with the name of C. Lyell[170] who elaborated it. His advocacy led to its wide adoption in Switzerland[171] (the erratics on the flanks of the Juras naturally suggested flotation and stranding by drift-ice), north-west Europe,[172] Great Britain[173] and North America.[174] It was especially espoused in eastern Canada where fossiliferous Champlain Clays and shelly drifts, and the terraces and beaches built by the modern drift-ice, caused Canadian geologists[175] to attribute more importance to submergence than did their colleagues in the United States. J. W. Dawson championed the view until his death in 1899 and G. M. Dawson[176] hinged Canada upon a north–south line along the eastern foot of the Rocky Mountains. He advocated the hypothesis for the plains of west Canada because the glacial theory was difficult to apply there and the glacial deposits were stratified and widespread.

Environment strongly influenced national thought in this matter just as, at a later date, it caused planation surfaces to be referred in North America to fluviatile degradation and in Britain to marine activity. Thus the drift theory was most strenuously defended by those who laboured in lowlands and coastal areas. In the British Isles,[177] it was naturally held by workers in Lincolnshire, East Anglia, Lancashire, Cheshire, the Welsh border, Isle of Man and Central Plain of Ireland and on the older drift of central England at a time when the glacial theory was accepted for the mountainous districts of Scotland where, generally, a shelly drift is absent and moraines and erratics, patently analogous to phenomena exhibited about modern Alpine glaciers, are profusely scattered throughout the Highlands. Similarly, geologists in the Netherlands, north Germany and Russian Baltic provinces persisted in this view[178] after those of Scandinavia had largely abandoned it. Even in Switzerland, the classical land of glaciers, the drift of the plain was thought to differ in origin from that in the mountain valleys[179]; the drift theory seemed obvious for the Plain of Lombardy.[180]

Few questions about the Ice Age excited more discussion than did the amount of the submergence. While the shore was inevitably drawn at the limit of the drift, as in North America[181] and at the Thames–Bristol Channel line in England[182]—this limit, however, was associated by some with the denudation of the drift farther south[183] or of the sloping ground against which the drift had been deposited[184]—the depth of the sea in the submerged tracts was uncertain. It was gauged by the joint testimony of the height of striae, deltas and erratics[185] and of high-level shelly gravels or of stratified gravels, sometimes interpreted as true beaches, which were without shells.[186] Figures ranged between 1000 ft and 4000 ft (*c.* 300–1200 m) for Great Britain,[187] between 3000 ft and 5000 ft (*c.* 900–1500 m) for North America,[188] and up to 2700 m for the Alps.[189] Russian and German geologists were content with modest figures for lack of summits which could register greater depths.

The causes of this submergence were as a rule non-catastrophic; they included the displacement of the earth's centre of gravity owing to alternate glaciation of the hemispheres[190]; the melting of polar ice resulting from increased obliquity of the orbit; isostatic depression under the ice-load[191]; attraction of sea-waters by the ice[192]; and subglacial cooling.[193]

In a variant of the theory,[194] which in identical or similar garb has not wanted later adherents, the striae were engraved by "mud glaciers" or by the drift which slipped as the land emerged from the glacial sea.

Objections. Objections to the drift theory are insuperable: Charpentier[195] demonstrated this as early as 1835. The motive power of bergs is provided

by winds and currents whose strength and direction vary in vertical planes so that bergs of different draught drift on different courses or at different speeds. Such erratic agents, with their unsteady rocking motion, could not, as Darwin[196] observed, produce dome-shaped rocks nor could they have inscribed the striae which run over large areas with striking regularity nor those which score overhanging faces or the lee sides of obstacles: these demand an impossibly nice adjustment of depth of sea and draught of berg. Inconsistent also are the rock-basins, giant-kettles, drumlins, crags and tails; the local nature and non-stratification of the till; and the erratics' angularity and their distribution in definite trains aligned with striae and drumlins. Nor is the theory in harmony with the soled and striated boulders (these are diagnostic if plentiful enough to permit the flatness ratio to be plotted[197]); with the orientation of big boulders[198] or the intrusion of till along bedding planes (see p. 364); or with the whole phenomena of marginal drainage, including those spillways, postglacially undeepened, which as in the British Isles[199] (near Dunbar, east of the Wolds, in the Kyle of Sutherland, south of the Solway, and in Ireland) descend to within 100 ft (30 m) of present sea-level.

Finally, it is irreconcilable with the topographical relations of the limit of the drift, as Charpentier emphasised, and with the restricted centres from which bergs could have radiated, since the glacier-covered mountains, if the submergence were appreciable, would be too small to furnish adequate quantities of drift-ice and too low to have a climate sufficiently severe.

Its champions[200] declared that accumulations resembling till were now revealed in the marine glacial clays recently elevated in arctic lands, e.g. on Kolguev Island,[201] or dredged from the Southern Ocean[202] where deposits with much glacial material cover a large area in the track of the icebergs in the south-west.[203] Evidence which might serve to distinguish between the products of ice-sheets and floating ice was then both scanty and inconclusive. More recent marine expeditions have helped to provide such diagnostic material though little is known even to-day of the character of marine boulder-clays. Research in the Antarctic,[204] where deposits of floating ice are best developed, has shown that typical glacio-marine sediments are free from lime and are distinguished by heterogeneity and lack of arrangement in the coarser constituents and, except near the outer part of the pack-ice, by a want of stratification due to rapid sedimentation. They also lack the hard parts of organisms when under pack-ice but enclose them in great quantities at its edge where they build up globigerina and diatom oozes.

Boulders, as in the North Atlantic, are apt to be embedded vertically,[205] while those collected from shore-ice, from bergs off Franz Josef Land, or from Spitsbergen's drift-ice are more definitely planed and polished on one side.[206] Floating ice, to judge from the floor of the North Atlantic, is unable to produce till-like accumulations.[207] Nowhere, except perhaps in Ross Sea, has the bottom of the Antarctic seas a deposit resembling land-ice till.[208]

Thus it seems that while drift-ice provides the raw material of boulder-clay, floe-till has a more homogeneous clayey basis and a more even texture with occasional traces of indistinct lamination; its embedded erratics are more uniformly distributed. The valves of its shells are often in apposition and enclose material exactly matching the surrounding matrix. Finally, the distribution, stratigraphical relations and surface expression are different.[209]

Perhaps the biggest obstacle of all is the absence of marine shells from the drift, unless broadly the ice was advancing from the sea.[210] Attempts by

"submergers" to account for this are unsatisfactory and unconvincing. Glaciers, it was said, excluded the sea from the mountain glens[211] or, re-advancing after the emergence, swept out the shelly drift they had previously deposited.[212] Alternatively, the submergence was so deep that it reached the "azoic zone" postulated by E. Forbes[213] in 1843 (this was before deep-sea dredging revealed a pelagic life) or was so rapid or transitory that molluscan and other life had not time to establish itself.[214] In another view the seas were too muddy or too poor in vegetable life or too dark under their ice-cover.[215] The belief that the waters were freshened and chilled[216] is quite incompatible with the known exuberance and teeming life, especially of individuals, in the cold lateglacial seas (see ch. XLV) and in polar seas to-day[217]; reaction currents occur off ice-fronts,[218] the isohalines are compressed in the return current, and the animal life is astonishingly abundant in consequence. Low temperatures favour a high gaseous content of the water, including CO_2, a higher quantity of mineral nitrogenous compounds, e.g. ammonia, nitrites and nitrates, and a remarkable longevity of life.[219] The amount of plankton is also influenced by the sea-ice.[220] The absence of sunlight and other conditions create a winter plankton under the sea-ice while about the edge of the ice there is a "spring colouring", i.e. an enormous amount of plankton, and in the open ocean a characteristic "summer" condition with less plankton. The unexcelled concentration of plankton in the Antarctic is the food supply of fish and directly and indirectly of seals and penguins and of the stupendous whale community. Pelagic foraminifera and diatoms are rare or absent from the bottom deposits beneath continuous pack-ice in both the Arctic and Antarctic[221] but are found in great abundance about its edge and are so plentiful in the upper layers of the ocean that they often colour the sea-ice yellow.

The lack of bored or barnacle-encrusted rock-surfaces or of true shell-beds and the rarity of pebbles bearing traces of marine action are equally at variance with the drift theory. Few erratics in the drift are encrusted with barnacles[222] or serpulae[223] or are bored,[224] these significantly being glaciated[225] or having their crypts filled, not with the surrounding till, but with fine sand rich in microzoa.

Finally, the arguments which combine to disprove the drift hypothesis establish glaciation by land-ice. That striae and roches moutonnées correspond exactly with those about modern glaciers makes the inference of like origin inescapable. The dominant surface forms of the drift are inexplicable on any other hypothesis—moraines down to sea-level display steep faces which have never been submerged.[226] Even the water-worn and stratified sands and gravels, which at first sight seem to countenance submergence, are essential to the glacial theory, since all the ice except a small fraction lost by evaporation was inevitably converted into water at its dissolution, and even the evaporation fraction was probably more than made good by marginal precipitation.[227]

3. *Glacial Theory*

Although glaciers were mentioned in writings of the ancients[228] and the word glacier was probably introduced into literature as early as 1507,[229] the scientific study of glaciers had hardly begun before the time of J. J. Scheuchzer (1707)—he observed the flow and stratification of glaciers and their transport

of debris—or indeed before de Saussure who towards the end of the 18th century added numerous facts to the then knowledge of Alpine glaciers as we saw on earlier pages. At the beginning of the 19th century, G. Wahlenberg[230] caused almost as much to be known of the Norwegian ice; he observed the downward creep of glaciers, the origin of crevasses including the bergschrund, the change from snow to firn, moraines and ice-scratches, and the turbid glacier-streams. Yet after the appearance of de Saussure's *Voyages*, with the noteworthy exception of the contribution by I. Venetz, the study of glaciers made little progress until the outburst of activity about the fourth decade of the century. This witnessed investigations by Agassiz, Desor and others on the Aar Glacier and by Tyndall and Forbes in Chamonix. The years 1840 and 1841 are indeed memorable in the history of glacial research: publications appeared in rapid succession by J. Fröbel, C. Godeffroy, C. Martins, C. M. Engelhardt, C. Rendu, L. Agassiz and J. de Charpentier.

The retreat of the Alpine glaciers in the middle of the century (see p. 145) led to a general endeavour to survey them in detail; F. Simony mapped the Dachstein, F. Seeland the Pasterze, E. Richter the Karlingerkees and Obersulzbachferner, S. Finsterwalder the Gliederferner, Gepatschferner, Suldenferner and Vernagtferner, A. Blümcke and H. Hess the Hochjochferner and Hintereisferner, H. Crammer the Übergossene Alm and A. Penck the Sonnblick Glacier. A new phase began with the founding of the Glacier Commission of the Swiss Alpine Club in 1869 and the systematic investigation of the Rhône Glacier (see p. 141).

An Alpine guide Deville early attributed erratics to transport by glaciers.[231] P. Martel (1744) and M. Besson (1780) described lateral and other moraines[232] though the honour of first recognising their origin belongs to Bordier.[233] J. A. DeLuc, N. Desmarest and de Saussure noticed almost simultaneously that glaciers transport material.[234] The polishing and grooving of rocks by ice was discovered about the same time: it was made by N. Sererhard[235] in 1749 and by other naturalists a little later.[236]

Early phase. The glacial theory, like many other scientific theories of note, occurred to several people at roughly the same time if not in quite identical form. The former great extent of the Alpine glaciers was deduced from striated rock-surfaces by K. Kastofer[237] in 1822 and from erratics and moraines beyond the ice by earlier naturalists.[238] J. J. Perraudin,[239] a chamois hunter of the Val de Bagnes in the Valais, noticed in 1815 the erratic blocks and the striations parallel with the valleys and imagined the Rhône valley filled with a vast glacier as far as Martigny. He it was, as Forel[240] suggests, who imparted the idea to Venetz and Charpentier. Venetz, first attracted to the study of glaciers when called in as an engineer to design an escape for the waters (Merjelen See) they impounded, developed Perraudin's idea in his *Mémoire sur les variations de la température dans les Alpes de la Suisse* of 1821[241]: he carried the ice as far as the Jura Mountains.

Charpentier,[242] seeking material to rebut the theory, was led by his own evidence to support it, especially in the classic publication of 1841 which incorporated his observations of 25 years. Completely establishing the former extent of the Swiss glaciers, he constructed the first glacio-geographical map. His confirmation of the observation, previously made by de Saussure[243] and others (see p. 615), that the valleys directed the striae and erratics, showed that glaciation followed and did not precede the upheaval as Agassiz[244] had

assumed. J. Hutton,[245] anticipating all other workers, also grasped the fact that the Swiss glaciers had spread far over the plains, and Playfair[246] in 1802 appealed to glaciers, "the most powerful engines without doubt which nature employs", for the transport of erratics. This he continued to do even more strongly when the close of the Napoleonic wars allowed him in 1816 personally to inspect the erratics on the Jura flanks.[247]

The idea of glaciation was also propounded at an early date for north-west Europe. J. Esmark,[248] who observed moraines, including Vassryggen ("Esmark moraine") at the mouth of Lysefjord (the first moraine to be described as such in north-west Europe), planed surfaces and rock-flutings, features all reproduced by existing glaciers, thought in 1824 that glaciers several thousand feet thick had extended out to sea and moved the granitic blocks now dispersed over Norway—S. Nilsson accepted this theory.[249] Eight years later, A. Bernardi[250] compared the north German erratics with those of Switzerland and pictured the country under the polar ice—the Siberian mammoths bore out the coldness of the climate. Goethe,[251] possibly independently but more probably relying on the conclusions of others, affirmed that glaciers had borne the north German erratics to their present positions.

As neither Playfair nor Esmark developed the glacial theory nor sought to strengthen it by additional facts, the theory languished: outstanding objections were the requirements of a frigid climate and the demand for glaciers of continental dimensions. Its acceptance for north-west Europe was delayed by the absence of stony moraines and of glaciers readily accessible for study. The clash with ancient doctrines and preconceived hypotheses and the "physical impossibility" of covering north-west Europe with an ice-sheet (a statement often repeated in later time) also retarded it.

Moraines, probably because they are less striking than giant erratics or osar, were not appealed to as arguments. Indeed, it was only after the land-ice theory had been accepted that they were sought and mapped, the tracing of them on the plains, where they little resemble Alpine valley moraines, being deferred to a much later date, e.g. about 1870 in North America.[252]

Louis Agassiz. Though the conception of glaciation by land-ice originated with Hutton, Playfair, Esmark, Venetz and Schimper, and its development was largely the work of Charpentier, its popularising was due to the energy and powers of exposition of Agassiz.[253] Others, however, drew the more important of the logical conclusions. Thus K. F. Schimper,[254] the poet-naturalist, was the first to suspect the existence of ice-sheets in the Ice Age (Schimper[255] proposed this name in 1837)—Charpentier dates the birth of the glacial theory from the publication of Schimper's poem. Yet Agassiz came to be regarded as the founder of the theory, notwithstanding his want of interest in the cause of the Ice Age and his crude catastrophic ideas—the Alps were raised suddenly through the ice-cover, broke through this, and flung the rocks on to it; the pre-existing fauna was destroyed and another one created.

This great Swiss naturalist, who first studied glaciers under Charpentier as a recreation from his work on fossil fish, gave his *Discours sur l'ancienne extension des Glaciers* before the *Société helvétique des sciences naturelles* on 24 July, 1837.[256] In this and in subsequent papers,[257] he pictured the whole of Switzerland under a great ice-sheet (*grandes nappes de glace*) and north Europe similarly enveloped during a period of universal cold which

imprisoned the Siberian mammoths in ice. The pronouncement owed much to earlier writers though it preceded by a few years the first descriptions of the Antarctic ice-sheet by J. D. d'Urville (1842), J. C. Ross (1846) and C. Wilkes (1848).

This bold and novel conjecture was one of the most far-reaching and fertile in the history of geology—Darwin,[258] writing in 1881, regarded it as the most striking step geology had made in the previous fifty years. It was indeed so vast that it met with incredulity or derision. Most of Agassiz's contemporaries, including in Britain the overpowering authority of C. Lyell, W. Whewell, H. B. De la Beche, G. A. Mantell, A. Sedgwick and R. I. Murchison, all of whom advocated drift-ice (see above), strenuously resisted it. Applied only to mountainous areas like the Vosges[259] and Pyrenees,[260] French and Austrian Alps,[261] and Iceland,[262] its immediate results were to make the antithesis no longer the diluvial hypothesis and to narrow the contest to one between glacialists and upholders of the drift theory.

Polar ice-caps. Reluctance to accept the glacial theory arose partly from the extravagance inseparable perhaps from a new theory of this scope and magnitude. Not only was the Alpine glaciation united with that of north-west Europe, as by Agassiz[263] (he subsequently abandoned the view[264]), North America glaciated from Greenland[265] and the ice made continuous across the North Atlantic,[266] but the whole glaciation was conceived as extending from "hemispheres of ice" about the poles. The polar or circum-polar cap, the creation of Bernardi, was attractively simple; it was the most plausible form of an ice-sheet.

These polar caps found supporters in Charpentier[267] and Agassiz[268] and afterwards in many British and other geologists[269]: the Hebrides, for example, were glaciated from the north-west.[270] By exaggerating the great cold, the caps even expanded into equatorial regions,[271] as into the Amazon valley and Brazil, Nicaragua, Jamaica, South Africa and Australia, or into a universal sheet filling the ocean basins.[272] Like the deluge (see p. 617), they annihilated all life, necessitating a new creation,[273] or drove it on to the low coastal plains, uncovered by draining away the sea to build the ice[274] (see p. 1355). Their melting produced the floods of tradition.[275]

These catastrophic extravagances, in so far as they had any evidential basis, rested upon the mistaken identity of exfoliation boulders or "nigger heads" with erratics and of desquamation surfaces with roches moutonnées as was shown, for example, for Brazil.[276]

The polar ice-cap, though occasionally advocated in recent years,[277] especially by those who centre the ice-sheets about a shifting pole[278] (see p. 1542) and reduce the size of the ice-sheets to small travelling ice-caps, was relinquished for two main reasons. First, the Arctic was not appreciably more severely glacierised than now since, as in north Greenland to-day, its precipitation was insufficient to nourish much bigger ice-masses.[279] Secondly, the ice-movements, as given by striae, erratics and osar, were not everywhere parallel or from the north but, as was early shown for Scandinavia,[280] diverged from a number of centres or "glacial radiants".[281] The crucial discovery that striations proceeded northwards on the arctic side of the centres was made in the north of the Kola Peninsula and about the White Sea by W. Böthlingk[282] in 1840 (the direction was actually from the north-west) and after a few years in north Scandinavia.[283] Similar outflows were postulated by Agassiz from British mountains (see below) and were later positively

demonstrated from striae and erratic trains going northwards in the Ox Mountains of Ireland[284] and in the Shetland Islands and Grampian Mountains of Scotland.[285] They were later established for the Vosges[286] and a north-westerly movement over the Swiss Plain had long been known (see p. 615)—the *phénomène erratique des Alpes* and the *phénomène erratique du Nord* were distinct and separate.

Comparable movements were discovered in arctic America much later; the transport in the Canadian Archipelago,[287] like the glaciation of the northern part of the western Cordillera[288] and the flow over the mainland's northern coast,[289] was from the south. Erratics from the limestone outcrops of the arctic islands are absent from the Laurentian country[290] whose northern coasts consist of Pleistocene sand and gravel,[291] a few hundreds of metres thick, with ice-rafted boulders and only mainland material.

The view that the carry was invariably from the north, as implied in Murchison's term Northern Drift (see above) and frequently advocated for Britain,[292] led to several false determinations of erratics,[293] e.g. that Aberdeen granite occurred in Co. Donegal, Scandinavian erratics in Galloway, boulders from the Western Isles in Loch Linnhe, and Kintyre rocks in the Vale of Eden.

A third and most convincing disproof of the circumpolar caps, an obvious corollary of the two already mentioned, was only discovered much later. It was then found that the ice in such northern lands as Alaska (see p. 729), Labrador and Greenland (see p. 726), Spitsbergen,[294] Russia and Siberia,[295] had a northern as well as a southern limit, and, as G. M. Dawson and R. G. McConnell showed for Canada, shrank southwards.

Switzerland. Apart from an occasional dissentient,[296] the drift theory was early abandoned for the Swiss Plain (Lyell[297] relinquished it after his visit in 1857) and had already yielded to the rival theory by the middle of the century when B. Studer, A. Guyot, E. Collomb and C. Martins realised the nature of the great morainic ridges of north Italy. Charpentier's arguments[298] and Studer's recantation[299] did much to accomplish this, though Guyot's detailed researches[300] upon the erratic distributions provided the finest proof. By tracing the boulders to their source, he found the order of succession of the Alpine peaks was reflected on the Swiss Plain in parallel lines of erratics (cf. A. Jaccard's map of the lines of ice-flow[301]). He discovered incidentally too that the great Helvetian ice was composed of several glaciers, each marked off from its neighbours by its erratics. E. Renoir[302] followed the glaciers outwards in the Dauphiné and A. Escher[303] published the first map of the Swiss moraines and areas of glaciation in 1845. The Chambéry meeting of the *Société géologique de France* in 1844, which Agassiz and Rendu attended, witnessed the final triumph of the theory in Switzerland.[304] A. Favre's map[305] (1875) of the Swiss Plain on which the extent of the various glaciers (Rhône, Aare, Reuss, Limnat and Rhine) was indicated by different colours, and those of later times,[306] together with modern Alpine researches, as in the German Alps[307] and the Salzach, Enns and Steyr regions,[308] have only served to strengthen it.

North-west Europe. The submergence hypothesis lasted in the Baltic region much later despite Escher's proof that floods produced entirely different results from those in glaciated countries[309] and the evidence of Agassiz, Charpentier and others that glaciers carry erratics and engrave

scratches indistinguishable from those of north-west Europe. Nearness to the sea and the seemingly incontrovertible evidence of submergence given by the shelly clays readily explain the tendency. Moreover, the strong faith which Agassiz's general lowering of world temperature and Ice Age demanded came less readily to north European geologists than did the belief in a mere extension of the present Alpine glaciers to their Swiss contemporaries.

Nevertheless, faith in the *Petridilauniska Flod* and in the palaeocrystic sea gradually waned. The difficulty of providing the waters, the radially dispersed erratics and diverging striae transverse to the morainic *Raer*,[310] combined with the zoogeographical observations of S. Nilsson[311] in Scandinavia, with the work of H. v. Post[312] on the moraines in Östergotland in 1854 and the important paper of O. Torell[313] (1859) for Sweden, and with the glacial researches of Rink[314] and others in Greenland, finally overcame both prejudice and honest conviction. They ensured the triumph of the theory in the Baltic countries.[315] An occasional dissentient,[316] including A. E. Nordenskiöld who never quite abandoned the drift hypothesis for Scandinavia, did not seriously detract from the victory's completeness.

The conversion was naturally retarded in north Germany which had few striated surfaces but had shelly drifts and intercrossing erratics[317] and lacked the high mountains whence ice could have come. In this the diluvialist von Buch[318] was not without influence. Yet the glacial theory had its adherents like G. v. Helmersen[319] who suggested that glaciers scored the Rüdersdorf striae[320] (discovered in 1836 by Sefström[321]). Johnstrup[322] also interpreted the drift ridges in Schleswig-Holstein as moraines and the disturbances in Möen and Rügen as products of ice-thrust (see p. 257). O. Torell,[323] who had studied glaciers in Switzerland, Iceland, Spitsbergen and Greenland, expressed the view in 1875 before the *Deutsche geologische Gesellschaft*: the Rüdersdorf striae smoothed the way for its acceptance. His paper, sustained by that of A. Penck[324] four years later, marked the turning point in the trend of German geological opinion. Belief in the land-ice became general[325] though the compromise of an ice-sheet, now on land, now afloat, found an occasional exponent.[326] It was strengthened by the discovery of striae near Leipzig and at other places near the inner margin of the North German Plain and by disturbances in the strata, though these were not so interpreted in Germany until 1880.[327]

The theory naturally found root somewhat earlier in continental Russia—it was advocated, for instance, by Inostranzeff (1871), F. Schmidt (1872), P. Kropotkin (1876) and S. Nikitin (1886)—and equally naturally, perhaps, was unable to displace the drift hypothesis in the Netherlands until 1881 and 1885 when F. J. P. Calker[328] postulated the glacial theory for that country and recognised the morainic nature of the Hondsrug.

France lay outside the glacial limits. Yet her geologists shared in a lively disputation on the origin of the Alpine and Scandinavian drifts; for as elsewhere opinion was divided: C. Martins[329] and E. Desor,[330] who with T. Durocher took part in the Spitsbergen expedition of 1838, supported Agassiz, though Durocher[331] favoured the view of Sefström. The announcement of the discovery of a cold fauna[332] in Auvergne and other places lent support to the glacial view. Falsan,[333] who with E. Chantre catalogued the erratics and striated surfaces of the Rhône basin,[334] has well described, with literature, the glacial theory's progressive diffusion in France both before and after 6 April, 1846, when Agassiz's lecture[335] before the *Société géologique de France* finally

gained the ascendancy for the theory in that country—de Lamothe[336] has recently (1930) postulated currents of water for the transport of erratics.

British Isles. Agassiz who came to England in 1840, primarily to study fossil fish, toured Britain with Buckland after the Glasgow Meeting of the British Association (1840). He communicated the results to the Geological Society of London in a paper *On Glaciers, and the evidence of their having once existed in Scotland, Ireland and England.*[337] The Highlands, Southern Uplands, Lake District, Wales, west Ireland and Wicklow Mountains had each their peculiar detritus and served as centres of radiation. They fed an ice-sheet that overwhelmed the land as in modern Greenland; he recognised striae, as at Ballachulish and at Blackford Hills, Edinburgh,[338] roches moutonnées near Kendal, Loch Awe and Loch Leven, and moraines near Kendal, Penrith and Inverary. The Parallel Roads of Glen Roy he interpreted as beaches in a glacier-lake (see p. 464). Buckland followed Agassiz the same evening, November 4th, with a paper on the *Evidence of Glaciers in Scotland and the north of England*[339] in which he courageously recanted his diluvial opinions. The debate which followed was lively[340] and presaged the opposition the theory was to meet in Britain.

Agassiz's visit convinced Lyell[341] that glaciers had debouched from the Grampians upon the low country of Angus and Darwin[342] that striae, roches moutonnées and perched blocks were relics of ancient glaciers in Carnarvonshire. Forbes[343] noticed glacier-marks on the Cuillin Hills of Skye, and traces of glaciers were found in the glens of Argyllshire by C. Maclaren[344] and in several valleys in south Scotland by W. Kemp.[345]

A partial relapse on the part of some of his British adherents followed Agassiz's departure from Britain. Thus Darwin[346] attempted to show that bergs were able to make rectilinear markings while Buckland[347] re-affirmed his original faith in diluvial waves and currents as at least part explanation of the phenomena. A transitional phase ensued, exemplified by many writings,[348] when land-ice and submergence were made successive. The British sequence was, first, extensive glaciation by land-ice; secondly, the "Great Submergence" during which the sea slowly or suddenly[349] rose to the upper limit of the shelly drift (see p. 630); and thirdly, a gradual re-emergence and ploughing out of the marine drift by a second set of valley glaciers.

Reports by the Boulder Committee of the Royal Society of Edinburgh (Proceedings, 1872–84)—the *Société helvétique des sciences naturelles* and the *Société géologique de France* had previously appointed boulder committees[350]—reflect the gradual change of view respecting the mode of carriage of the erratics; earlier reports invoked ice-rafts, later ones local glaciation. The conversion was accelerated by the reports of the Erratic Blocks Committee of the British Association, published annually between 1873 and 1913: they brought out the dispersal of the erratics from certain centres. British opinion was slowly confirmed in its belief; milestones were A. Geikie's paper on Scotland[351] (1863), J. Croll's essay on the boulder-clay of Caithness[352] (1870) and first application of ice-transportation to the dispersal of Shap granite erratics[353] (1871) and R. H. Tiddeman's first really decisive attacks on a submergence of England[354] (1872). The glacial theory alone satisfactorily explained the phenomena in such mountainous areas[355] as Scotland, Wales, Donegal and the Lake District as well as on lowlands,[356] e.g. Caithness, Holderness, East Anglia, Vale of Clwyd and the Central Plain of Ireland. While opinion was still unfavourable at the Glasgow Meeting of the British

Association in 1876 (the Glasgow Meeting following that which Agassiz attended), the end of the century, thanks in no small measure to the advocacy of H. C. Lewis[357] and P. F. Kendall,[358] saw the land-ice conception almost undisputed.

Nevertheless, submergence has claimed recent adherents[359]; the nature of the boulder-clay, its included foraminifera and perfect shells have with other facts led to a resuscitation which increasing faith in isostatic oscillations has only encouraged. Yet only a very small minority are so persuaded. With certain exceptions, such as the figure of about 2000 ft (600 m) occasionally demanded,[360] the depth now postulated is much more modest. Gregory,[361] its main advocate, suggested a 400-ft (120 m) submergence of central Ireland and others[362] one of 500 ft (150 m) for Scotland at some time during the period, mainly on the evidence at Clava (see p. 1013).

Although most of the early "submergers" ran the shore-line along the limit of the drift in the south of England and left the southern counties dry, the modern tendency is to submerge these: Holst,[363] for example, submerged them to 200 ft (60 m). A pre-Sicilian or early Pleistocene submergence in southern England (possibly about Norwich Brickearth time) of *c.* 540 ft (165 m) has been claimed on the grounds that erratics, among them pebbles from Devonshire, Cornwall and the Mendips, have strayed to Boar's Hill and other localities near Oxford,[364] erratics of augite picrite from Cornwall to 400 ft (122 m) on the Mendips,[365] and a granite boulder from Cornwall to 600 ft (183 m) on the South Downs.[366] Drift-ice, it is suggested, passed up the Bristol Channel and through gaps in the Chiltern Hills into the Upper Thames (in the contrary direction to Croll's Great Baltic Glacier which over-rode southern England from the east[367]). The tourmaline- and cassiterite-bearing rocks were almost certainly derived from the Bunter pebble beds of the Midlands by ice moving southwards.[368]

In recent time too it has been claimed that the North Sea glaciation in East Anglia was an episode in the middle of a marine transgression[369] and that the tills of Holderness were laid down in water as is implied by the presence of sodium chloride in inland boulder-clays[370] and by the horizontal persistence of certain lithological characteristics in narrow horizons over a wide area and the interstratification of boulder-clays and marine sands.[371]

North America. Agassiz's influence was felt in North America mainly after he arrived there in 1846 and applied his theory to the White Mountains and the Great Lakes.[372] Though championed by his Swiss compatriots,[373] the theory found only a few American adherents[374] and E. Hitchcock, who had early adopted it,[375] following the reading of Agassiz's paper in London (see above), like Buckland in England, recanted,[376] largely because of Murchison's criticisms and Lyell's visit in 1841 and 1842.[377] Yet J. D. Dana's advocacy[378] in 1855 and subsequent years led to its general acceptance, though it was not until 1867 that it became universally recognised and was made the basis of field investigations. Its tardy recognition was partly owing to theological opinion[379] and in part to the great uplift of erratics (see p. 370) and the absence of mountains in the centres from which these came. Nevertheless, North American geologists later became radical glacialists as their work usually lay far from the sea. They grouped the drifts according to their arrangement and relation to physical features rather than to lithological composition which, because of the display of their structure in countless natural and artificial sections, has formed such a feature of British glacial literature.

Yet the glacio-natant hypothesis was significantly retained, even by such convinced glacialists as Dana and Agassiz,[380] for the Atlantic littoral. The shelly drift of Boston,[381] for example, from which 55 different species have been now obtained, was regarded as proof of submergence until W. Upham,[382] applying the conclusions of Lewis and others in Britain (see below), affirmed that ice had dredged it from the adjacent sea-bottom.

Shelly drifts. Objections to the glacial theory are few and are serious only in so far as our knowledge of the present ice-sheets is imperfect. The nourishment of Pleistocene ice-sheets, it is said, is climatically impossible[383] and their flow over irregular terrain (a difficulty frequently raised since Durocher[384] first did so) or over vast plains with little or no gradient or with reverse slopes demands powers on the part of the ice which, it is averred, are inconsistent with its known qualities. Even Charpentier was unable in his later years to repress a feeling of uneasiness concerning the glacial hypothesis.[385]

Shelly drifts (kitchen-middens have been mistaken for them[386]) are widely distributed in coastal parts of the British Isles. They are found from Cleveland to East Anglia,[387] in the Cheshire Gap between the south Pennines and north Wales,[388] and along the northern and western coasts of Wales[389] from Anglesey to Pembrokeshire. In Scotland,[390] they occur in Caithness, Banff, Aberdeenshire, north of Berwick, Wigtownshire, Rhinns of Galloway and coastal Ayrshire and at the Butt of Lewis (see p. 1013). They are also found in the Isle of Man[391] and in coastal Ireland,[392] viz. in the north-east between Lough Foyle and Carlingford Lough, southwards to Co. Wexford and Co. Cork and at Glenulra and Belderig, Co. Mayo. Reports from inland localities[393] (Naas, Roscrea, Maryborough, Greenhills and Ballinasloe) lack confirmation.

Britain's classical deposits are east of Macclesfield at 1280 ft[394] (390 m) on the west flank of the Pennine Chain, at Gloppa near Oswestry at 1120 ft[395] (340 m), and at the Three Rock Mountain, Dublin at 1200 ft[396] (366 m). At Moel Tryfaen,[397] the most celebrated of them all, the current-bedded shelly gravels, discovered by J. Trimmer,[398] lie on the first rise of ground above the Menai Strait at 1281 ft (*c.* 390 m) and contain many molluscs and foraminifera. The history of opinion of this deposit epitomises British theories on the subject; floods,[399] e.g. waves of translation, bergs,[400] pack-ice,[401] coast-ice,[402] the sea[403] and an ice-sheet (see below) have all been invoked.

The marine shells of the British drifts, with the noteworthy exceptions of Kintyre and Clava (see p. 1013) where they form shell beds, are disseminated throughout sands, gravels or clays. Of the numerous molluscan species, *Cyprina islandica*, *Tellina* and *Turritella* are perhaps the commonest—representative lists[404] are those of Caithness, Aberdeen, Cheshire, Lancashire, Gloppa and Howth. Foraminifera, referable to species of moderate depth and seas slightly colder than off-shore at present,[405] are widely distributed,[406] having been recorded from Ireland and the Hebrides in the west to Cambridgeshire in the east. Hyaline in appearance and empty of mineral matter, they mingle with ostracods and sponge spicules[407] in sands filling the inner whorls of *Turritella* and cavities which *Saxicava rugosa* has bored. *Nonionina depressula*, which forms one-half of the specimens, and *Polystomella striata-punctata* are the two most characteristic and abundant species. Associated with the molluscs and foraminifera are the terminal joints of crab claws, ray and disc plates of starfish, spines of *Echinus* and *Spatangus*, and occasional barnacles and serpulae.

The German drifts have yielded freshwater shells,[408] and those which border the Baltic[409] from Russia in the east to Denmark in the west contain marine shells and foraminifera.

Shelly drifts have been discovered along the Atlantic seaboard of U.S.A. (see above) and of Canada,[410] e.g. at Cape Cod, in Queen Charlotte Islands, and in the St. Lawrence valley. Foraminifera, borne by wind with other dust from marine flats west of the continent, have been recorded from Saskatchewan River and other places in the heart of Canada up to 1900 ft[411] (*c.* 580 m). Marine shells occur in clays and the underlying beds in Patagonia up to 10 m[412] and in boulder-clays in north Siberia.[413]

Croll[414] and Tiddeman[415] were the first in Britain to assert that the shells had been dredged up by ice advancing over the sea-floor. This explanation was later applied by T. F. Jamieson[416] to Aberdeen and by T. Belt[417] and others[418] to the classical high-level sites mentioned above. The shells, as Lewis[419] emphasised, were merely "shell pebbles" or erratics, like the transmarine erratics with which they are associated,[420] such as Lake District andesites, Eskdale granite, Galloway granites and Ailsa Craig microgranite found at Moel Tryfaen with other erratics of Welsh derivation.

Their erratic nature is overwhelmingly proved: the bivalves are seldom united or in apposition, the epidermis is rarely preserved and the shells are generally comminuted, often to mere "crumbs". Perfect specimens are usually minute, like the foraminifera and the small gastropods, e.g. *Trophon* and *Fusus*. Yet the long delicate spines of *Polystomella crispata* are finely preserved in the drift about Glasgow[421] and diatoms and sponge spicules in that of Cape Cod.[422] Such perfection is compatible with glacial transport; for the enveloping sand, gravel or clay was probably frozen hard before the ice enclosed and carried them englacially.[423] This is conclusively demonstrated by the perfect shells, with uninjured epidermis, found in similar masses recently transported in South Victoria Land, in the smaller Arctic islands, and in Greenland and Spitsbergen.[424] Fragile Cretaceous foraminifera have been carried about 130 miles (*c.* 210 km) from Canada to Montana.[425]

The finely polished and striated state of many of the shells and their attenuation into white streaks constitute further proof.[426] Moreover, the shells are sometimes filled with material differing from that which surrounds them[427]; those in clays frequently have sand under their umbos when in apposition or between the valves, while foraminifera often lie in nests or pockets of sand.

The mingling of species of different temperatures also demonstrates glacial transport from a sea-bottom. Cold and warm forms are intimately associated, as in the Isle of Man[428] ("submergers" postulate variations in the depth and currents attending movements of the land[429]) though the assemblage in any one locality, while often retaining the impress of cold conditions, may, as Forbes[430] noted, differ somewhat from that in an adjacent area or on another horizon. Thus the shells at Ballyrudder, Co. Antrim, at Elie in Fife, in the Basement Clay of Holderness, and in the Scandinavian drift of Co. Durham are arctic[431] in character while the assemblages in Caithness and in the Cheviot drift of Co. Durham and in the Boston drift of North America (see above) are warmer[432] and may represent the sweepings of a preglacial or interglacial sea. Specimens of different habitat and predilections are also intermingled,[433] e.g. freshwater and marine, shallow and deep water, shingle mud, sand and rock-haunting species.

Of similar import are the markedly southern or Pliocene shells of many British drift localities,[434] e.g. Aberdeenshire (suggestive is the fossiliferous limestone of supposedly Coralline Crag age dredged from a submerged outcrop 80 miles (*c.* 130 km) east of the Orkney Islands[435]), Kintyre, Isle of Man, Cheshire, Holderness, Co. Carlow and the Wexford Gravels of south-east Ireland,[436] and the shells of the region of the north Italian lakes.[437] Derived foraminifera, such as the Cretaceous specimens in the drift of Mecklenburg[438] and various parts of the British Isles[439] and the Cretaceous bryozoa of the Korallensand of Schleswig-Holstein,[440] provide confirmation.

Shell-banks on the sea-floor were involved where an ice-sheet crossed the

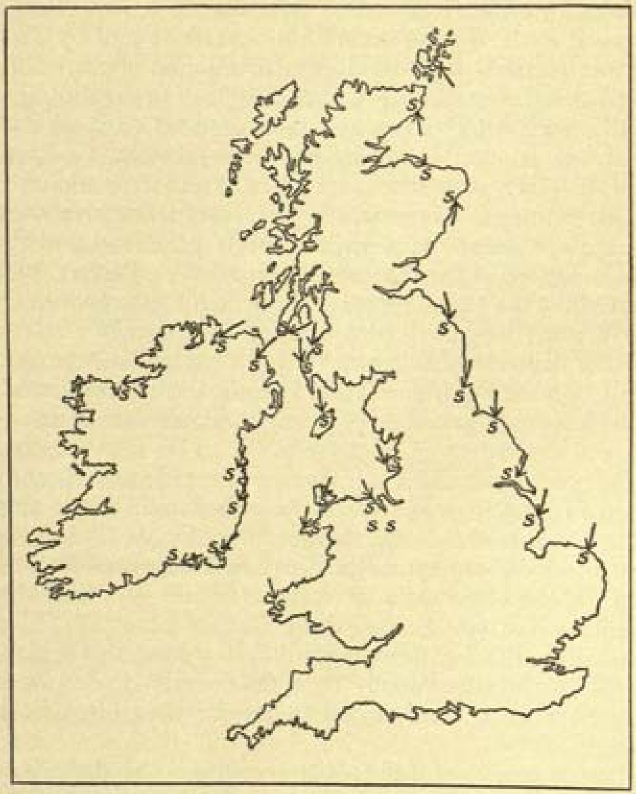

FIG. 113.—Distribution of the British shelly drifts and their relation to the invading ice.

sea-bottom or received accessions from ice which had already done so. The distribution of the British shelly drifts is ample proof of this (fig. 113), as are the well-rounded pebbles of some coastal drifts, e.g. Caithness, and the high percentage of clayey matter in their lower layers.[441]

Conclusion. The vague surmises, crude generalisations, grotesque assumptions and uncontrolled phantasies of the infancy of geology have given way to a body of well-supported inductions; the disastrous cataclysms have yielded to an ordered sequence of events. The glacial theory, at first only a working hypothesis, has by the most searching scrutiny and rigorous criticism been raised to the position of a fundamental doctrine of geology. Though

not without its difficulties, it explains better than its rivals a wide range of phenomena and has behind it the cumulative force of a vast mass of evidence.

Researches in Greenland and Spitsbergen are of the highest value in sustaining its interpretation of the various complex problems connected with the Ice Age while the present Antarctic ice-sheet, almost as vast as that postulated for Pleistocene North America, has removed the element of incredulity which in some minds attached to so striking a theory.

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Chapter XXXI

PLEISTOCENE METEOROLOGY AND CLIMATOLOGY

Despite the great advances of the present century towards a satisfactory reconstruction of Pleistocene meteorology and climatology, these aspects of the Ice Age remain but imperfectly known. Differences of opinion still exist upon such fundamental factors as the configuration of the lands and seas (see ch. XLIV), the position of the poles (see ch. LI), the earth's mean temperature, and the position and direction of the ocean currents, cold and warm (see p. 1093). Uncertain too is the behaviour of the climatic zones in lower latitudes, the climatology of which will be discussed separately (see ch. XLI).

In attempting such reconstructions, the glacial epochs only are generally concerned. The interglacial epochs were climatically as in most other respects "normal" or essentially the same as to-day (see pp. 917, 1535); in interglacial Europe, for example, chemical weathering prevailed, rainfall exceeded evaporation, rivers were eroding strongly, and moors, heaths, meadows and steppes were variously distributed. The "great interglacial" was probably slightly warmer and moister[1] (drier?[2]), as in the semi-arid plains of North America.[3] Oceanic conditions in western Europe are indicated by the Brörup deposits of Denmark (see p. 951), by the plants of the interglacial beds of north Germany and by the deep weathering of its drifts.[4] A milder climate in this region is suggested by the *Juglans regia* (now wild in Greece and Armenia) and in north France by the *Buxus sempervirens*, *Ficus carica* and *Cercis siliquastrum*. The treeline in the last interglacial epoch in the Alps was probably 300–400 m higher.[5] The climate of the interglacial epochs has been regarded as continental[6]—Milankovitch in his latest writings calculated the summer temperature of the Riss-Würm interglacial as 5·5°C higher, the temperature of the winter as 3·5°C lower. The monsoons of Asia may have been stronger[7] (cf. p. 543).

During the warmer interglacial epochs, the subtropical high pressure zones, with their dry and relatively storm-free conditions, were broader and extended further polewards; the climatic belts and zonal wind systems were also shifted polewards and were weakened; the anticyclones about the poles disappeared and were replaced by cyclonic centres; the polar climates were milder; and the Arctic basin had no ice (see p. 1536), except possibly in the shallower parts during the winter season. The climate of the interstadials was in general transitional between that of the glacials and the interglacials.

In true perspective, the glacial epochs being much shorter than the interglacial epochs (see p. 918), the Pleistocene as a whole was warm or genial; its glaciations were interruptions or episodes.

The climatology has been discussed incidentally by many writers, e.g. E. Geinitz,[8] and for many circumscribed areas, e.g. Scandinavia[9] and China.[10] Extensive reconstructions have, however, rarely been attempted. Those which have been essayed have unfortunately, with only an occasional exception,[11] been vitiated by a fundamental error in a primary assumption or

postulate, e.g. that the continents east and west of the North Atlantic Ocean were alternately glaciated,[12] that the poles wandered,[13] or that polar wandering was combined with continental displacement.[14]

To reconstruct the climatology we require a knowledge of the distribution of the chief meteorological factors, namely, temperature, pressure, precipitation and air circulation. Of the last three little is known and the first, about which so much has been written, is still only inadequately investigated. Although attempts have occasionally been made to draw isothermal lines[15] (see figs. 212, 213), our knowledge remains of a general kind: the Pleistocene temperature was so many degrees lower (see below), and the isotherms, as now, differed probably in latitude on opposite sides of the North Atlantic[16] (for the southern limit of glaciation was 10–12°C farther south in North America than in Europe), as they did on opposite sides of North America where the two most important ice-centres were arranged from north-west to south-east following the direction of the present isotherms.[17] While the nature of the vegetation and the altitude of the snowline help to give some definiteness to the isotherms, these and other factors offer little scope to arrive at figures for precipitation, pressure and winds.

Indicators of the climate are palaeontological, i.e. the flora and fauna, and physical, e.g. the snowline and periglacial phenomena.

1. *Lower Temperatures*

A warmer period? It is contended that the glacial epochs were not colder but warmer than now.[18] Thus hippopotamus and other warm animals resided permanently in Europe and in great numbers throughout the Glacial period[19]; the animals that lived on the edge of the ice-sheets were bigger than their living representatives[20] (see p. 798); many New Zealand species could not tolerate frost[21]; and the bottom waters of the present Mediterranean, which may serve as a Pleistocene minimum thermometer for this region,[22] have a temperature of 13°C. The warmth was related to a different distribution of land and water,[23] e.g. an increased submergence in lower latitudes,[24] an open Arctic basin,[25] or a higher solar radiation[26] which nourished the ice by augmenting evaporation and precipitation.

Paradoxically, the Antarctic's greater ice-sheet of the past (see p. 735) was associated with a milder climate[27]—*le froid tuerait les glaciers.* To-day, the snowfall is highest in summer (see p. 666) and both precipitation and glacierisation are heavier in the Balleny Islands than in the colder and more southerly South Victoria Land—extreme cold reduces the humidity of the air and both marginal ablation and snowfall. A severer climate would merely induce greater sterility since the snow crystals, which in the present Antarctic stick together at higher temperatures,[28] would be converted into ice and become a ready prey to the wind. The upper snowline was then higher.[29]

Simpson[30] estimated the Antarctic temperature as 4°C above the present and correlated this glaciation with warmer epochs in all quarters of the globe (see p. 1549). The higher temperatures were attributed to a strengthened air-circulation[31] (see p. 676) or correlated with the earlier phases of glaciation, the present cold being referred to the later phases.[32] Under certain conditions, warmer winters will increase snowfall and encourage the growth of ice-sheets[33]; this is especially true of those regions where the winter temperature is only a little below freezing point.

Nevertheless, this hypothesis is challenged by those who link the former Antarctic glaciation with diminished wind-velocity[34]; with a lessened gradient of the rock-floor, occasioned by tectonic tilting[35] or by glacio-isostatic subsidence and an extramarginal bulge[36]; or with a general strengthening of the cyclones which increased the precipitation and warmed the air so that the general lowering of temperature was not felt here.[37] Others ascribe that glaciation in Graham Land, Tierra del Fuego and other southern regions to more intense cold[38] which made the ice less viscous[39] and, by expanding the area of sea-ice, caused violent storms to be less frequent, reduced ablation, aided the growth of hoar-frost and slowly expanded the ice.[40] The great cold may have reduced the rate of flow in the central part of the ice-sheet which would therefore have thickened during the glacial epochs synchronously with glaciers elsewhere.[41] Alternatively, the present Antarctic climate may be peculiar to that continent and due to its abnormally low snowline and excessive coldness.[42]

Although the lower glacial sea (see ch. XLIV) favoured more extensive glaciation in the Antarctic as elsewhere by reducing calving and melting, its responsibility for the greater Antarctic glaciation[43] is unlikely; the configuration of the adjacent sea-floor and the signs of severer glaciation in the continent's interior suggest it was merely a minor factor.[44]

A moister period? The Pleistocene, it is averred, was not only warmer but moister[45]; it was a Pluvial period or Snow Age,[46] glacial only where it was cold enough.[47] The heavier precipitation was related to the planet's motion,[48] to vulcanicity,[49] to higher temperatures (see above), to stronger air-circulation (see p. 676) and therefore greater evaporation from the sea,[50] or to a lower level of the mountain barriers of Asia[51] (see p. 605). Alternatively, the earth's water-surface was greater[52] or there were local submergences like the Aralo-Caspian Sea that favoured glaciation in the Caucasus, Tienshan and Pamirs[53]; a connexion between the Baltic and White Sea that drowned the plains of north-west Europe[54]; a flooding of the Sahara[55] (disproved by A. Pomel[56] and K. v. Zittel[57]—the shells about Timbuktu were introduced by man and those in Libya probably by birds[58]) and of the Plain of Lombardy that nourished the north Italian glaciers[59]; and the widened Bering Strait which admitted warmer waters to the Arctic basin north of Siberia and enlarged the glaciers in Arctic regions.[60] Greater precipitation in winter, because of solar radiation and a lower summer temperature due to heavy clouds, caused the glaciation of Siberia and central Asia.[61] It has been estimated[62] that an average increase in precipitation of *c.* 25%, was a consequence of Milankovitch's variations.

This view of a moister climate, which was plausible at a time when most geologists believed that maximum glaciation coincided with widespread submergence (see ch. XXX), has been more recently restated for Alaska,[63] arctic Canada and north Greenland,[64] for middle latitudes,[65] including South America and central Asia, and for Kilimanjaro, Java and the tropics.[66] Justification is sought in the retreat of the modern glaciers of Tibet[67]; the nature and distribution of the Pleistocene mammalian fauna,[68] with its large herbivores and implied abundant vegetation, and the survival of its Africo-Asian element into the last glacial epoch[69]; the character of the molluscs in the German loess[70]; the wider distribution of the mangrove in Pleistocene South America[71]; the Pleistocene flora of Switzerland which, resembling that of to-day, implied a depression of the forest-line by 200 m only[72] (cf. p. 1072)

and an oceanic climate with milder and more humid winters and colder and cloudier summers and the same mean annual temperature as now.[73]

It is further contended that the precipitation-maximum coincided with glaciation and was primary[74]; that a maritime climate is essential for any extensive glacierisation[75]; that the Scandinavian glaciers would dwindle were cold currents to replace the present warm ones in the North Atlantic[76]; that modern arctic glaciers lie mainly in regions of heavier condensation and of warmer ocean currents, as in Alaska,[77] with its annual precipitation of up to 254 or even 482 cm. Moreover, further cooling would starve the Antarctic ice still further (see above); the Pleistocene ice stagnated during the retreat[78]; and the precipitation at the centres of the North American ice-sheet, east and west of Hudson Bay, would have to be raised since its annual amount in Labrador to-day is only 7·6–15·2 cm,[79] and in the Antarctic was 110 mm against the present annual figure of 40 mm.[80] The oscillations of modern glaciers[81] (cf. p. 151), the small Pleistocene depression of the central African snowline,[82] and the Pluvial period of lower latitudes (see ch. XLI) strengthen, it is said, this conclusion.

Precipitation is without question indispensable to glacierisation. Its influence was essential in Siberia and in polar latitudes and can be seen in the following facts: 1 million cu. miles (*c.* 4 million cu. km) of water must be evaporated to build the Greenland ice-sheet[83]; 75–90% of the surface of the Canadian Archipelago is nearly free from snow at all seasons (V. Stefansson) and there are no glaciers on other regions of deficient precipitation,[84] including Labrador, e.g. the Torngat Mountains over 1800 m high, the interior of Alaska, Grinnell Land, the highest parts of Tibet and of north Greenland (this is a high-arctic desert so that plants are unable to live because of the scarce precipitation and the low humidity of the air during summer)—the annual precipitation in west Greenland diminishes as follows: 61°N., 124·1 cm; 64° 10′ N., 65·4 cm; 69° 15′ N., 22 cm; 72° 45′ N., 21 cm; and 81° 41′ N., 10 cm—on Wrangel Island and the New Siberian Islands, and at the "cold pole" of Siberia where the temperature at Werchajansk in January, 1892, was −67·8°C[85] (mean January temperature −51·2°C) and more recently at Omaiko was −71·3°C.[86] There is no ice in central Spitsbergen and little in the south where a cold arctic current is inserted between the coast and the warm Gulf Stream waters—farther north, where the cold current is absent, the glaciation is considerable.[87] Moreover, in Pleistocene times, north Greenland (see p. 726) and parts of Alaska (see p. 729) were without ice; the ice on Wrangel Island (*c.* 600 m) failed to reach the mainland[88]; and the glaciation diminished northwards in Scandinavia where, for example, during the first phases, the outermost islands at the Arctic Circle were ice-free.[89] To-day the glacierisation increases in Iceland into the moister south and in the Alps into the moister west. The conditions most favourable to glacierisation are found not at the North Pole but at about 75° N. Latitude and especially in the region of the North Atlantic, e.g. Greenland, Iceland and Spitsbergen. The moisture of the Pleistocene climate in Europe is seen in the character of the tundra vegetation in the central European corridor[90] and in the swollen rivers,[91] though reduced evaporation, following upon the low temperature (together with melting snows and saturated ground, as in the modern Alps[92]), may be the immediate cause of this—the ratio of run-off in Europe may have been increased from 25–30% to 60–80%.[93]

Nevertheless, precipitation alone cannot explain either the Glacial period

or the glacial succession. To be the sole factor, it would have to be excessively, almost catastrophically high.[94] It could only induce glaciation if cold lowered the snowline and brought the ground within its influence. Lands which to-day have heavy precipitation or snowfall, such as Hawaii, South Georgia, the Falkland Islands and Kerguelen (which has one of the most oceanic climates in the world), had bigger Pleistocene glaciations.[95] Moreover, mountains now relatively arid had only a very moderate lowering of the snowline[96]; the present snowline is highest in arid regions,[97] is generally parallel with that of the Pleistocene (see below), and maintains the same interval above the forest-line[98]; tundra and not forest inhabited central Europe[99] (see p. 1070); and the Pleistocene glaciers in their cross-sections were related to their fluviatile successors.[100]

Penck's objection[101] that the firnfields of the central Alps, as Richter first noticed,[102] were apparently no fuller during glacial time, though supported palaeobotanically[103] and by recent calculations of the precipitation in the Pleistocene Alps[104] based upon M. Lagally's formula (= 10–20% less), is not rigorously conclusive. Even had they been fuller, the névés might have left no trace on the steep faces of the cirques[105]—the thinner ice may have been plucking and not abrading.[106] Only a small difference in height is to be expected because the ice and snow levels converge into the interior,[107] as the nunatak region of Greenland demonstrates,[108] and the zone of maximum precipitation is principally depressed in the marginal belt[109] which had most precipitation[110] (see p. 665). J. Maurer's observations[111] that very little snow falls during the sunny winters in the very high Alps above 3000 m, when unusually heavy snows fall at lower levels, also seems to remove the basis for Penck's assumption.[112] According to some botanists,[113] this region, which was a floral "refuge" (see p. 1391), had in glacial times a smaller precipitation, a relatively warm summer and a strong insolation. It is, however, probable that the total precipitation was the same but was differently distributed.[114]

Primary fall of 5–7°C. Contrary to Penck's belief[115]—he argued, for example, that the known maximum depression of the snowline (1200–1300 m) gave a fall of temperature less than is demanded (8°C), and that the lower temperature would cause less evaporation and therefore condensation—there was probably more precipitation during glacial time,[116] e.g. in regions as far apart as north Chile,[117] equatorial Africa,[118] Siberia[119] and Antarctica.[120] To what extent this was general remains to be discovered. While no doubt primarily related to the changes which brought about the general cooling,[121] it was partly secondary: the cold depressed the snowline into the zone of maximum precipitation (see below), induced condensation at lower levels and strengthened the air-circulation by steepening the pressure and thermal gradients (see p. 676). Yet the supplement was mainly fictitious: the precipitation was differently distributed (see above) and a higher fraction fell as snow.[122]

The Glacial period originated in a world-wide fall of temperature[123] at all seasons[124] but especially during the summer months (see p. 647): the optimum conditions for glacier-formation are cool summers and long, snowy winters.[125] The snowline was universally depressed (see p. 652); the eastern and western sides of the South American Cordilleras were, as now, sharply contrasted[126]; the glaciers had a similar distribution[127]; the Atlas region had colder molluscs[128] and Morocco was cooler[129]—man here lived in caves.[130]

Himalayan species spread to the high hills and plateaux of Peninsular India[131] and *Rhinoceros sondaicus*, *Bibos sondaicus* and certain birds to Java[132]; Malaya was slightly cooler[133]; and the temperature of the inner tropics during the last glaciation was 23°C,[134] corresponding to a fall of *c.* 4°C; the *Dryas* flora was widespread in Europe (see p. 1066); and a rising summer temperature occasioned the ice-retreat (see pp. 647, 1147). The Pluvial period was due not entirely to increased rainfall but to lessened evaporation associated with lower temperatures.[135] Although this may have caused the bigger volume of the Pleistocene rivers[136] (see above), it is not positively established that the reduction in evaporation which the acknowledged fall of temperature brought about was appreciable[137] according to W. Knoche's tables.

The amount of fall is given by the Pleistocene depression of the snowline as computed for many parts of the world (see p. 652) but most accurately for the tropics[138] where it was 500 m. Using the commonly accepted lapse rate of 0·5°C for every 100 m (the anticyclones and their more frequent temperature inversions may have lowered this ratio[139]) this depression of the snowline gives a lowering of only about 2·5°C, though data for other latitudes give a higher figure since the extratropical depression averaged apparently 800 m,[140] e.g. in south-west Ireland and near Cattaro. Estimates of the fall vary between 3° and 12°C[141]: the inconsistency between them is explained by variations in latitude and altitude and by the secondary effects, which some glacialists hold were responsible for most of the fall.

Corresponding figures are given by the displaced isochional lines of Europe (see p. 655) which yield 6–7°C (allowing 100 m or 0·5°–1°C for the lower sea-level), and by the treeline in central Europe drawn on the assumption (not always accepted[142]) that the vertical interval between treeline and snowline remained constant (see p. 1071). Confirmation is supplied by the Driftless Region of Wisconsin (see p. 727) which was below the snowline, although its mean annual temperature is now only 5–6°C; by the nature of the land flora and fauna, e.g. in the British Isles[143] and in California[144] (= 11·1°C); by the breadth of the marginal belt of the coral seas in which the glacial chill killed the corals (see p. 1092); by the temperatures in Greenland to-day[145] (= 7°C); by the contrast between oceanic and continental climates, a method used by J. Probet and M. Semper and followed by A. Woeikof[146]; and by Milankovitch's calculations[147] (= 8°C).

Thus while the early glacialists thought the change that caused glaciation was drastic (Agassiz[148] spoke of a *frisson terrestre*) later researches have shown (as C. Martins and J. D. Forbes first surmised[149]) that the *primary* fall ("astronomic displacement"[150]), as distinct from the much severer fall the ice-sheets themselves induced (see p. 676), was relatively small. The figure may have lain between 5° and 7°C so that the oscillation of mean temperature between glacial and interglacial epochs may have approximated to 7–9°C. Milankovitch's calculations (see p. 1544) give the reduction in the solar radiation during the summer half year as 4·6°–5°C in the temperate and polar latitudes of the northern hemisphere.[151]

Its effectiveness. The various elements which control climate are so nicely balanced that a slight alteration or maladjustment leads to serious and disproportionate disturbances. A small cooling, therefore, was able to promote glacial conditions[152] since a fall of 6°C corresponds to about 800 miles (*c.* 1300 km) of horizontal movement—Charpentier[153] thought that 700–800 cold and wet years like those from 1812 to 1818 would be sufficient to carry

the Alpine glaciers and erratics to the Jura Mountains, and L. C. W. Bonacina[154] has suggested that the British Isles lie quite uncannily near reglaciation: a fall of 1·7°C would cause small glaciers to form on Ben Nevis. The effectiveness of a depression only a few times that which accompanies Brückner's period (see p. 133) or 10–20 times the difference between the temperatures at sunspot maximum and minimum[155] is suggested by the recession of the present Alpine glaciers. These have shrunk within two or three generations in a conspicuous degree (see p. 142), although meteorological data hint at only a slight climatic change,[156] possibly because precipitation varies inversely at higher levels.[157] Since the maximum advance of last century, they have decreased in area between 6% and 20% and even 27·3% in the case of the Paznaun,[158] in depth, as on the Mer de Glace, by 50 m,[159] and in length by 400–500 m or even exceptionally 3·2 km.[160] During this withdrawal, the snowline rose 100 m in the French Alps[161] and 60–150 m in the Eastern Alps,[162] 150 m in the Zillertal Alps,[163] 200 m on the Sonnblickkees and other glaciers,[164] or one-third or one-half the rise since the Daun stage of the Pleistocene retreat. Other figures,[165] which differ among themselves because of aspect and other factors, are 50–70 m, 60–115 m and 145–210 m. The corresponding rise in the Himalayas (Nanga Parbat) has been 50 m[166] and in the Andes 150–200 m[167] (see p. 151). The rise this century in the Ben Nevis area is probably about 100 m[168] (see p. 15).

Some glacialists, therefore, not surprisingly, have thought that the changes which induced glaciation did not differ qualitatively from those of Brückner's periods and merged into those of the plurisecular variations of historic time (see p. 150) and the pulsations of ever smaller amplitude that are superimposed upon them[169]—during sunspot maxima and glacial epochs the meridional type of circulation was more frequent, during sunspot minima and interglacial epochs the zonal type dominated.[170] This view, however, has been assailed on the grounds that the fluctuations during the Glacial period should have been greater and not least at the equator,[171] that the glacial epochs, unlike Brückner's periods, were cool and relatively dry,[172] and that the sunspot activity would have to be increased to an improbable extent since the effect falls off rapidly as the relative number of spots increases.[173]

The cooling was effective because it lessened the evaporation on both land and sea,[174] increased the percentage of snow in the total precipitation (see above), and lowered the snowline into the zone of maximum precipitation. Once formed, the ice by a reflex action accentuated this result: Tyrol and other Alpine areas furnish examples of greater glaciation due to the hemming of flow by physical barriers and the passage of high plateaux from below to above the snowline[175]—the valleys became "overglacierised" (Ger. *übervergletschert*). In effect, the ice lifted the surface regionally through some hundreds of metres, extending the ice far beyond what the climatic change alone justified; it augmented the precipitation, cooled the air, steepened the temperature gradient, initiated katabatic winds, and raised the wind velocities. The amount of "uplift" depended upon the component heights and extent of the surfaces of the *Stockwerke* of peneplained surfaces. Possibly as little as 100 m separated the snowline of the last glaciation in the British Isles from that of maximum glaciation.[176] The ice and snow in summer caused the sun's heat to be expended in melting without appreciably influencing temperature.

One important factor was the vast expanse of highly reflecting snow and

ice[177] which increased the earth's total albedo,[178] now estimated at 40–45% (forests and oceans, 3–5%; frozen old snow, 70%; melting snow, 60%; ice, 50%; and clouds, 80%), by possibly 3–4%, thereby depressing the world's temperature by possibly 4°–4·8°C[179] and, acting alone, depressed the snowline of the northern hemisphere by possibly 600 m[180]. Additional factors were the extensive cover of sea-ice which, though it may have diminished the precipitation,[181] weakened the influence of the sea in middle latitudes—the air over a large floating ice-sheet is 20–30°C colder than that over a water-surface under similar conditions[182]; the lowered sea-level which reduced the exchange of waters over the Wyville-Thomson Ridge (cf. p. 1536) and in effect made the land higher; and the shift of the Gulf Stream (see pp. 1093, 1536). In short, the final temperature in the glaciated countries was out of all proportion to the small initial cause (see pp. 676, 1072).

The chilling was the more efficacious since it was felt mainly during the summer months[183] which were subject to frequent night frosts. Such summer cooling lengthened the frost season, reduced the summer melting and augmented the percentage of snow. It is proved for lateglacial time by the varves[184] of Scandinavia and North America and is suggested by the distribution of modern glaciers and by the following figures (in degrees C) of glacierised and unglacierised lands to-day[185]:

	Glacierised					*Unglacierised*			
	Antarctic (Graham Land)	Antarctic (Gaussberg)	West Greenland (Godthaab)	East Greenland (Angmagssalik)	Spitsbergen	Norway (Brönnö)	East Siberia (Yakutak)	Alaska) (Prince of Wales)	North Canada (Mackenzie)
Warmest month .	0°	−1°	6°	6°	4°	13°	17°	10°	13°
Coldest month .	−16°	−22°	−10°	−11°	−20°	−2°	−47°	−23°	−28°
Year . .	−7°	−11°	−2°	−2°	−8°	5°	−14°	7°	−8°

South Siberia, in the same latitude as south Greenland, is without ice although its mean annual temperature is *c.* 9°C lower, and north Siberia has glaciers only on its highest mountains, viz. in Saigan, Chersky, Kamchatka, Anadyr and Karyak mountains. In the peninsula of Labrador even the tableland of the Torngat Mountains (59° N. Lat.) which stands at 4000–5000 ft (1200–1500 m) nourishes only a dozen little cirque glaciers at present, though the winter occupies two-thirds of the year and snow falls every month of the summer.[186]

Nevertheless, it may be that this lowering especially in summer, even when combined with greater precipitation in winter and with the effects of the ice, cannot account for all the facts in our possession. The North Atlantic coasts, whose mean temperature now lies between 8°C and 0°C and whose warmest month has tempertures of 17°C to 12°C, had then a mean annual temperature below −10°C and a warmest month at freezing point.[187] To explain this remarkable change and the deployment of ice-sheets over the plains of Europe and North America may require some factor additional to a general lowering

of world-temperature. The lowering, however, increased the precipitation (see p. 676) by increasing the evaporation (notwithstanding the diminution caused by the greater cold[188]), by raising the intensity and life of the cyclones (see p. 1134), and, in effect, by lifting the general altitude of the continents through glacio-eustasy. The glacial epochs doubtless varied considerably in their coldness and moisture[189]: Penck's glacial curve (see p. 919), for example, is not a pure temperature curve.

Siberian climate. The problem of Siberia's Pleistocene climate is particularly obdurate. It turns very largely upon the Asian glaciation (see p. 720) and its cause, upon the conditions under which the Siberian mammoth lived, and upon the relation of this animal and its contemporaries to the layers of ground-ice (see p. 564).

Mammoths roamed widely over north Siberia[190] They inhabited almost the entire north coast, including Taimyr, Janaland and the New Siberian Islands, and wandered eastwards as far as Manchuria and Kamchatka and, in smaller numbers, southwards to Lake Baikal and the Vilui River. Only one is recorded from southern Siberia, viz. near Nijni Udinsk, and none beyond the high ranges bounding the desert of Gobi on the north,[191] though the carcases are much more restricted, only two, the Ides and Hertz mammoths, having been found south of the Arctic Circle (three of the four frozen rhinoceros carcases occurred south of this line) and most of them 250–500 miles (400–800 km) north of it.[192]

Their prodigious numbers may be gauged from the fact that in places, as Middendorf[193] said, the ground is "sown" with mammoth bones and teeth. During the last 250 years, Siberia has yielded the tusks of at least 50,000 mammoths[194]—each tusk may be 4 m long and weigh 200 kg, though the weight lessens northwards as the animal became smaller (see p. 808). Its ivory, known as far back as the 4th century B.C.,[195] is at present supplying about 50% of the world's ivory,[196] mainly from the ivory "mines" of the New Siberian Islands.[197]

Many conjectures have been made as to how the Siberian mammoths died. The early belief that rivers swept them down,[198] especially at spring floods or on the ice,[199] is readily disproved: the bones betray no sign of attrition; the animals throughout the tundra are frequently upright in posture; the New Siberian Islands have yielded countless milk molars and an occasional milk tusk[200]; and the northern bones and tusks are of a smaller race. Hence, the mammoths died where they lived.[201] Yet how they died remains conjectural. They may have broken through the ice when crossing streams[202] or have fallen through surface snows[203] or into ice-crevasses,[204] as the position of the corpses, the broken bones and the frozen blood indicate—significantly, frozen carcases of smaller animals have not been found, only those of the mammoth and woolly rhinoceros which presumably were too big to extricate themselves. They may also have been trapped in mudstreams set free by the thawing of the ice and frozen ground which a rich heath vegetation rendered invisible when the animals visited the river banks.[205] Thus there are clear signs of suffocation,[206] such as the erection of the penis and the brown coagulated blood that filled the blood vessels and fine capillaries of woolly rhinoceros.

Death took place, to judge from the occurrence of seeds and the nature of the undigested food in the stomach, during the late summer and early autumn.[207] Alternatively, the animals may have been overcome by a sudden climatic change[208] or overwhelmed by snow-storms,[209] as their frequent

orientation in a definite direction, the state of their blood vessels and nostrils, and the stomachs distended with food suggest.[210] A mouthful of grass between the teeth of the Hertz mammoth, not yet swallowed, proves that death was quite sudden.[211]

The mammoths on the north coast are interbedded with ground-ice[212] and are associated with "muck" or clays which contain plant remains,[213] e.g. *Alnus fructicosa* and *Betula nana*, and were formed subaqueously or subaerially by the decay of vegetable matter and the deposition of silt.

Mammoth on the one hand and ground-ice on the other have led to diametrically opposite conclusions concerning the climate which even a belief in the mammoth's wide powers of periodic migration fails to reconcile. A climate very like the present[214] seems warranted since the fossiliferous beds bear no sign of glaciation[215] and the stomach and teeth contain undigested food and plants[216] which include grasses, sedges, young conifer branches, small birch and willow, wild thyme (*Thymus serpyllum*), beans of *Oxytropis*, seeds of alpine poppy (*Papaver alpinum*) and of a boreal variety of the Meadow Rue (*Thalictrum alpinum*) and other species typical of the meadow flora of north Siberia to-day. The animals occurred in enormous numbers and are well fed, even over-fed. Their splendid physical state, as observations[217] on the physical state of the Spitsbergen reindeer show, is quite compatible with the present floral and climatic conditions.[218] The beasts probably kept to the neighbourhood of trees for shelter from the piercing winds and blinding blizzards and to be near their winter food supply. The frozen mammoths are found on the timbered banks of rivers and in a soil that nearly always contains fragments of trees. Bacterial decay was hindered by the cold climate and by quick interment in fine silts.[219]

Signs of a cold Siberian climate are equally unmistakable; for the burial of carcases when life became extinct and their preservation in an undecomposed and frozen state ever since[220] suggest a permafrost across 80 meridians and 12–20 degrees of latitude—putrefaction however seems to have started immediately after the animal's death and before burial[221] despite the small precipitation of the time. In keeping with this view are the mammoth's covering, as Cuvier emphasised,[222] the floral exchange between the arctic tundra and the Altai,[223] the Alpine and subalpine plants in widely separated mountains in China,[224] and the discovery, the first made east of the Baltic lands, of fossil arctic plants in 59° 59′ N. Lat. on the Irtysh (see p. 1066). These floral distributions go to prove that the Siberian forests were once pushed several degrees farther south.[225]

Most writers postulate a milder climate,[226] possibly because the continent extended northwards in glacial time[227] (see p. 1357), and a climatic displacement of from 20–40° of latitude.[228] The conclusion is based upon the following: plant remains, including the butternut (*Juglans cinerea fossilis*), have been found in the lower part of the River Aldan in freshwater sands with partially fossilised trees and mammoth bones—the butternut, which in North America does not grow south of the isotherm of 5°C, is found fossil in Siberia near the cold pole of Werchajansk[229]; large trees, more than 6 m long, and comprising genera which need longer summers than now to ripen their fruit, seed and wood, have been discovered in Siberia[230] and in the treeless Seward Peninsula of Alaska[231]; birch, far north of its present range, occurs between two boulder-clays at the northern end of the Ural Mountains[232]; the shape of the mammoth's tooth points to young twigs and small branches of

conifers as food[233]—in summer, the Siberian mammoth was probably a grass-eater[234]; fossil land and freshwater shells of species now living farther south have been found; and *Loxodonta antiquus*, *Mammuthus trogontherii*, *Elasmotherium sibiricum*, *Cervus euryceros*, *Camelus*, sp., *Panthera spelaeus* and *Crocuta spelaea* have been discovered in the lower Irtysh[235]—this is the only Siberian locality where Pleistocene animals that preceded the lateglacial animals are known.[236] The charcoal found in palaeolithic sites in the Yenisei establishes a climate no colder than the present.[237]

Vast herds of mammoth and other animals (the New Siberian Islands in the far north of Asia have yielded mammoth, woolly rhinoceros, musk ox, saiga antelope, reindeer, tiger, arctic fox, glutton, bear and horse among its 66 animal species[238]) required forests, meadows and steppes for their sustenance, as P. S. Pallas, C. Lyell, J. F. Brandt, A. v. Middendorf and F. v. Wrangel observed, and could not have lived in a climate like the present (see above), with its icy winds, snowy winters, frozen ground and tundra moss the year round.

The warmer period may have been postglacial[239] or preglacial[240]—North American pines grew preglacially in the lower Omoloi valley and in other localities (see p. 1087)—but generally belonged to the great interglacial epoch[241] following the glaciation represented by the underlying fossil ice. The climate was both warmer and moister[242] as the exchange of the Altai and tundra floras (see above) and the raising of Lake Baikal by 1000 m above its present level[243] bear witness. This moisture was due partly to the Aralo-Caspian Sea[244] (probably negligible in its action[245]) and the boreal transgression[246] (see p. 959), but chiefly to a more general cause, including the passage of cyclones, deflected by the European and North American glacial anticyclones[247] which in Siberia travelled eastwards along the Atlanto-Arctic front. The glaciation of Siberia and central Asia can only be explained by milder winters and cooler summers with heavier summer snowfall and less ablation.[248] The polar front of summer was intensified and shifted southwards through some hundreds of miles[249]—winter precipitation was inhibited probably even more than now. The piedmont glaciers, being higher and colder than the present land, caused increased precipitation upon them.[250]

2. *Snowline*

Altitudes. The Pleistocene cooling is best measured by the Pleistocene snowline. This varied locally with the orographic conditions, such as the lowering which the Adriatic caused in the Dinaric Alps,[251] and is only ascertainable from small peripheral glaciers or from those of the lateglacial phases.[252] Ice-sheets, ill-defined in size and shape, defy any attempt at calculation. In any case, as in the Alps,[253] they may have had not a snowline but a snow-zone, resembling that in the present Arctic (see p. 8).

The snowline obeyed the present laws (see p. 18). It rose from the poles towards the equator though most decidedly in the subtropics, the rise being not only general but also in particular regions, e.g. Jugoslavia, where on mountains with unilateral cirques (east side) it rose from *c.* 1800 m in 46° 14′ N. Lat. to *c.* 2300 m in 40° 58′ N. Lat.[254] It was domed over the mountains, e.g. in central Kurdistan[255] and in the Alps,[256] including the "postglacial stages". The rise, both equatorwards and mountainwards, was

steeper and more pronounced than to-day.[257] The line rose too from west to east in each mountain group in middle latitudes, e.g. in the British Isles[258] (fig. 114)—it fell from *c.* 600 m in the Pennine Chain to 380–400 m in western Ireland and possibly to 100 m in the Outer Hebrides—in the south Carpathians,[259] Tatra,[260] Balkans (see below) including the Dinaric Alps[261] and Albania,[262] the Pyrenees,[263] the middle zone of the Iberian Peninsula[264] (see

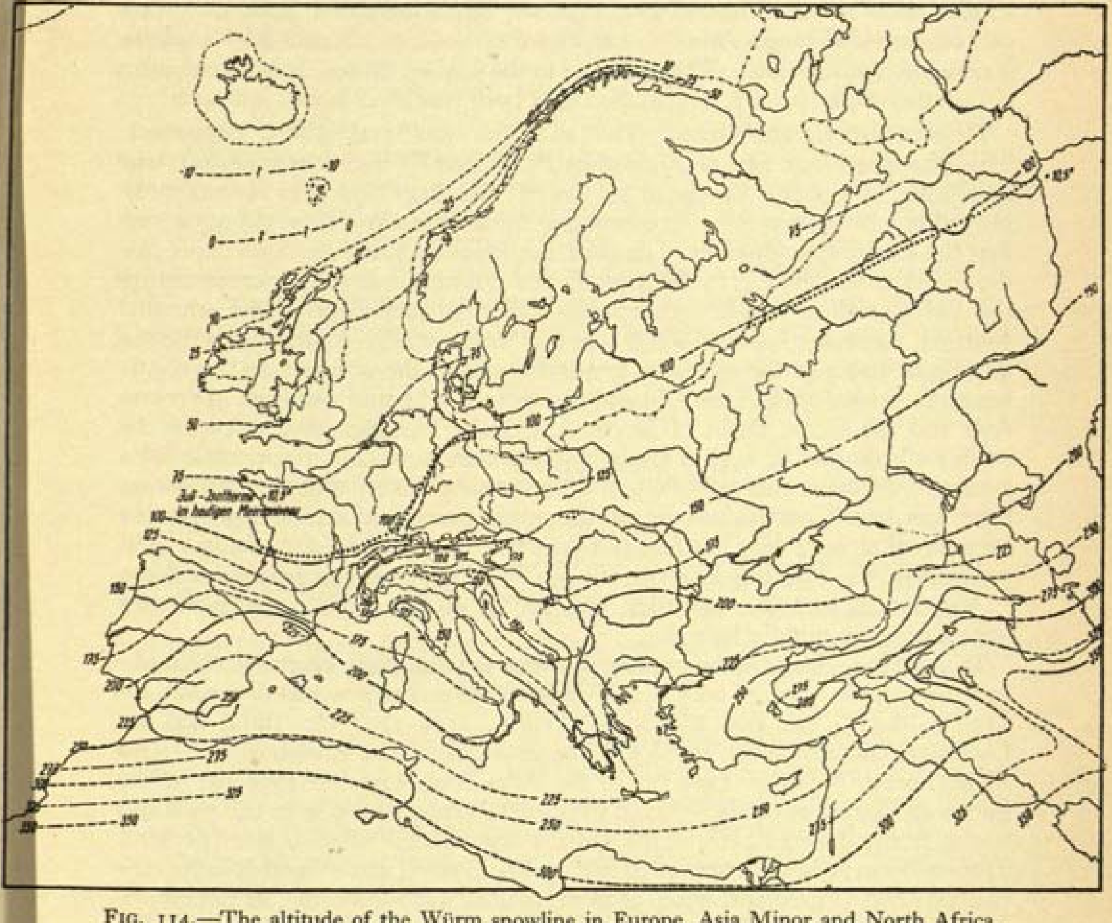

FIG. 114.—The altitude of the Würm snowline in Europe, Asia Minor and North Africa. Line of crosses = 10·5°C July isotherm (reduced to present sea-level). Lines of dots, coarser and finer = limit of Würm ice. J. Büdel, *1872*, p. 107, fig. 3.

below), Asia Minor,[265] central Kurdistan[266] and in the Caucasus[267] whose snowline both north and south lay 1200–1300 m higher in the east than in the west. Figures from the German Mittelgebirge[268] display this rise very well: Black Forest, 580–650 m (900 ?); Rhön, 750 m; Harz, 690–800 m; Erzgebirge, 950 m; Bohemian Forest, 1000–1100 m; Riesengebirge, 1150–1200 m. In the north Tatra[269] it stood at 1450–1600 m (depression 1000 m).

The easterly rise throughout Europe and the Mediterranean region is expressed in the following altitudes[270]: Vosges, *c.* 800 m; Auvergne, *c.* 900 m; eastern Alps, 1500 m; Hohe Tatra, eastern Carpathians, Bosnia and Dalmatia, 1800 m; Transylvania, 2000 m; Mount Olympus, 2200 m; Lebanon, 2500 m;

and north-west Persia, 3300–3400 m or 4000 m. The rise eastwards and equatorwards in the Iberian Peninsula is illustrated by profiles[271] and by the following data[272]: Sierra de Gredos, 1800 m in the west, 2000 m in the east; Picos de Europe, 1400–1500 m; Castillian watershed, 1800–1900 m; Sierra Nevada, 2400–2500 m (or 2850–2950 m). The height in Corsica was *c.* 1650 m,[273] in the central Apennines *c.* 1800 m[274] (southern Apennines, *c.* 2000 m), in the Atlas Mountains, 1900–2200 m.[275] The Balkans betray a similar rise[276]: west Montenegro, 1500 m; Rila Mountains, 2200 m. The rise continued through Asia[277] except in the east, e.g. Kamchatka,[278] where it rose into the interior. The snowline in the United States, as is revealed by cirque-floors (see pp. 17, 296), descended both northwards and seawards.

Depression of snowline. The snowline was everywhere depressed. This important fact, first recognised by F. Simony[279] in Salzkammergut, was elucidated by Penck's European studies[280]: Brückner and later investigators proved its universality.[281] In estimating the amount, it is to be remembered that the strong development of cirques, inherited from the Ice Age, depresses the snowline to-day, e.g. in the Alps,[282] as it did in this and other areas during the last glaciation[283] when compared with preglacial time. The amount, contrary to earlier assertions,[284] was not uniform.[285] It decreased in the middle latitudes of the northern hemisphere from the oceans into the continental interiors, both in the Old and the New World, and was least in central Asia and the Great Basin of North America. The increased value of the earth's albedo (see p. 647) in arctic latitudes may have been responsible for a greater depression there,[286] though it seems more likely that the depression here was small, partly because of the small precipitation and because the snowline is already very low (see p. 15) so that only a slight depression would push it to the limiting level of the sea.[287] The amount may have been *c.* 360–600 m in arctic latitudes, 600–900 m on equatorial mountains and 900–1200 m in middle latitudes.

In the Alps,[288] where the present snowline is principally known in the inner and the glacial snowline only in the marginal zone, the line was depressed by 1300 m during the Riss glaciation (Würm, 1100–1200 m; Bühl, 900 m; Gschnitz, 600 m; Daun, 300 m). The lowering in the British Isles[289] and Black Forest[290] was *c.* 1200 m; in the Atlas Mountains,[291] 1300 m; in the Sierra da Estrela of Spain,[292] 1100 m; in the Pyrenees 1200 m in the west and 700 m in the drier east[293]; in the south Carpathians,[294] 850–950 m (present, 2400–2800 m; glacial, 1650–1850 m); in the Hohe Tatra[295] and Rila Mountains,[296] 800 m (present, 2900–3000 m; glacial, 2100–2200 m); in Greece,[297] 1100–1200 m; in the Balkans generally,[298] 1000 m; and in the Apennines[299] at least 1100 m and possibly 1300–1400 m. In the Caucasus,[300] it lessened eastwards in accord with the general tendency for these latitudes (west, 1200–1300 m; north, 1100 m; centre, 600–700 m). In west Turkestan and north-west Persia it was 700–1000 m[301] and in Asia Minor about the same.[302]

In the Himalayas,[303] the amount was *c.* 500 m—alternative figures[304] are first glaciation 1600 m, second glaciation 1500 m, third glaciation 1400–1500 m and fourth glaciation 900–1000 m—in the Karakoram Mountains[305] 600 m, the Pamirs[306] 500 m (1500 m ?), central Tienshan, east Pamirs and west Kuen-lun 800 m,[307] and in the dry interior chains 400–500 m,[308] Kuen-lun[309] 600–800 m, west Tienshan[310] 600 m (1200–1400 m ?), Alai[311] 600 m (900–950 m ?), Russian Altai[312] 800–900 m (1200 m ?), east Altai[313]

1200–1700 m (Würm: 800–1400 m), west China[314] 1200 m, Kamchatka[315] 1000 m, Japan[316] and Hawaii[317] 700–800 m.

North American figures are not readily ascertainable since few glaciated regions are glacierised; they include the Sierra Nevada and volcanic peaks of Oregon, the Cascade Mountains of Washington, and the highest summits of Wyoming and Montana—they give a lowering of about 800 m.[318] In the Andes,[319] the figure varied between 700 and 1250 m and in Australia[320] between 900 m on Mount Kosciusko and 1500 m in Tasmania.

The depression diminished eastwards in each mountain group. This is exemplified in the Pyrenees, Caucasus[321] (difference, 300 m), Dinaric Alps,[322] Himalayas, Altai and Feghan Alai[323] (600 m in west; 400 m in east).

To these two laws, which Partsch[324] detected for Europe and F. Machatschek[325] extended into Asia and North America, Penck[326] added a third, namely, that the tropical depression was smaller, probably because of the strong summer ablation. In equatorial Africa and the Cordillera Real it was 500 m,[327] a figure probably representative of the tropics in general,[328] since it was 400–500 m in Peru and Ecuador[329] and in central America[330] in 10° N. Lat. (Ixtaccihuatl,[331] 800–900 m). According to others,[332] the displacement of the snowline in the moist tropics was very large, namely,

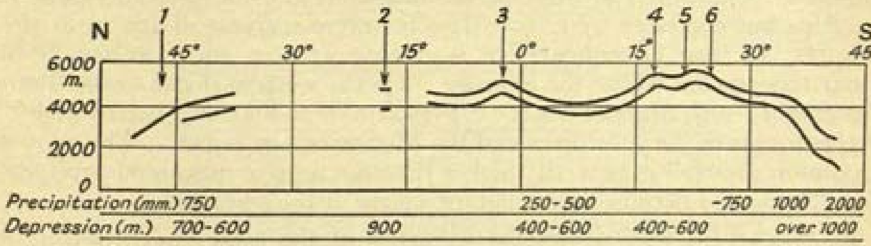

FIG. 115.—The present (upper line) and Würm snowline (lower line) in the American Cordilleras. 1, Rocky Mountains; 2, Mexico; 3, Pan de Azucar; 4, Ilimani; 5, Chlorolque; 6, Atacama. *1821*, p. 335, fig. 157 (after F. Klute).

1200 or 1300 m. R. Spitaler,[333] from astronomical considerations, gave it as 800–900 m.

Klute[334] discussed the depression very fully; his diagrams were taken along three approximately equidistant meridians; curves C (fig. 115) and D are along the western and eastern sides of the American Cordilleras. He estimates the snowline in the Arctic at 600 m, in the Antarctic at a few hundred metres (very uncertain figures), between latitudes 45° and 60° at 1000–1700 m, and in the subtropics at 400–600 m, with 600–800 m at the equator. These figures ignore the fall of sea-level of *c.* 100 m and assume that mountain ranges have maintained the same height, which in many cases was not so (see ch. XXIX), for example, in the Alps,[335] Iberian Peninsula,[336] Pyrenees[337] (probably), Anatolia[338] and the Sierra Nevadas of North America.[339] Earth-movements took place on such a scale that determinations of Pleistocene snowline altitudes which ignore them ignore a capital factor. Thus Pleistocene earth-movements explain why in the German Mittelgebirge, in the Mediterranean, including the Apennines, Sierra Nevadas, Atlas Mountains, Anatolia and the Balkans, as well as on Ruwenzori and in parts of South America, only one glacial epoch and that the last is present[340]—the traces of earlier glaciations, if they existed, may have been covered or

effaced by the last glaciation; why the Riss is the maximum glaciation in the Swiss Alps (see p. 1041); why in W. Ramsay's opinion (see p. 1537) interglacial epochs interrupted the succession—erosive forces required successive uplifts to cause glaciation; and why the earliest glaciation is missing from the Caucasus.[341]

Volcanic activity may also have disturbed the altitudes, e.g. in Jan Mayen (see p. 725), in Etna and the Aleutian Islands, and on Fujiyama in Japan.

Zone of maximum precipitation. The depression was most in the moister regions[342] where the zone of maximum precipitation was at a favourable height. The annual precipitation in a mountain range, as proved in the tropics and occasionally outside them, increases up to a certain altitude and then diminishes.[343] The height of the maximum depends upon the season, the temperature at the mountain foot, the vertical lapse rate, the relative humidity, the height of the clouds, the relief and situation of the mountains, and the strength of the insolation. The exact position is known in few cases. It is less than 1000 m in the tropics and about 1500 m in the temperate zone[344]—Himalayas 1300 m, Black Forest 1300 m, Jura Mountains 800 m, Hawaii 700 m. In the Alps,[345] it is 1500–2000 m and rises into their interior, e.g. Pre-Alps 1300 m, Mont Blanc 2500 m, and seems to reach the highest summits, though the snow-free period lengthens into the less rainy parts of the Alps but decreases by *c.* 10·5 days for every increase of 100 m in altitude.[346] In west Greenland[347] it is at 2000–2500 m and may usually be about 100–200 km within the ice-edge. On the western slopes of the Sierra Nevadas of North America it is at 1500–2000 m[348] and is exceptionally high[349] in the dry air of the subtropics and the Mediterranean region. The zone of maximum snowfall is generally higher than the zone of maximum precipitation,[350] possibly because of the lighter weight of the snow flakes.

A. Wagner,[351] who denies the existence of the zone for extra-tropical regions, ascribes the phenomenon to the action of rising winds at high altitudes which prevent the ordinary snow gauge from measuring the total snowfall.

The importance of the zone in connexion with the Pleistocene snowline was stressed independently by Klute[352] and Paschinger.[353] The latter showed that when the snowline was lowered into it (the Alpine snowline is 400–500 m higher[354] and is only below it when the snowline is exceptionally high at 3000 m[355]) not merely a cooling but an added snowfall resulted which automatically expanded the firn and ice-surface and lessened the ablation. As soon as the snowline entered the zone, glaciation became decisive and ever-increasing surfaces passed into the reservoir.

The polar snowline is now mostly below the zone but crosses it between 55° and 65° N. Lat. (or 50° N. Lat.[356]). Paschinger equated the crossing with the snowline's sudden jump in Scandinavia, e.g. Hardangerfjord, 400 m, north Norway, 1500 m, and the similar one in the Andes (fig. 116). An equal fall of temperature manifestly lowered the snowline by amounts that varied according to the snowline's relation to the zone.[357] Where this is now the lower of the two horizons, as in polar regions, little change ensued but a big one occurred in middle latitudes and near the coasts where the positions were reversed[358]—the Scandinavian and North American ice-sheets were situated just in this zone. Thus during the Wisconsin glaciation, the snowline stood 600–700 m lower in the Rocky Mountains and 1000–1400 m

lower in the Cascade–Sierra Nevada.[359] The lowering in coastal districts induced drier conditions farther inland.[360]

The zone was favourably placed in the tropics but unfavourably in central Asia. The existence of mountain barriers athwart the ice which, as in modern Patagonia[361] and in the Pleistocene Alps (see pp. 646, 717), raised the surface of the ice into the zone of nourishment had a similar effect.

Apart from these general movements, the snowline was locally abnormally depressed in territories peripheral to the ice-sheets since these created additional refrigeration (see p. 676).

Isochional lines and climatic displacement. Penck[362] constructed for Europe an isochional map displaying lines of equal elevation of the snow-line, for both the present and the Glacial period (cf. fig. 7, p. 14; fig. 212, p. 1073). The isochional line (the term *isoglacihypse*[363] is perhaps more

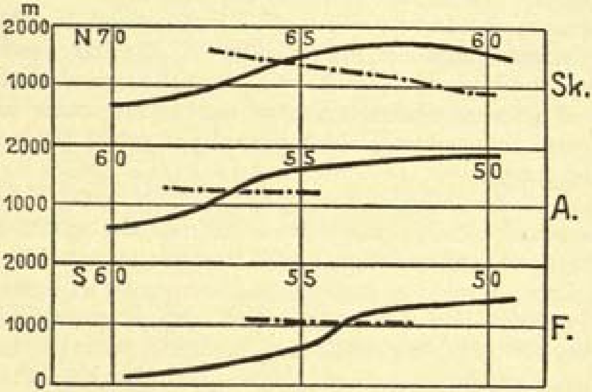

FIG. 116.—Diagram of the snowline (continuous line) and zone of maximum precipitation (dot and dash) in Scandinavia (Sk), Alaska (A) and Tierra del Fuego (F). V. Paschinger, *1252*, p. 37, fig. 2.

happily chosen) of 1000 m which to-day runs from north Norway to 64° N. Lat. and leaves the Norwegian coast in 59° N. Lat. was then pushed southwards by 1200 miles (almost 2000 km) to the northern edge of the Alps, south France and north Italy, leaving Europe in north-west Spain in 40° N. Lat. By an easterly shift through 1400 miles (*c.* 2250 km) it crossed the Ural Mountains in 62° N. Lat. The 1400 m line, now in Sweden, lay during the Würm glaciation in the Tatra while Cattaro on the Adriatic (42° 30′ N.) had practically the same snowline as present-day south Norway in 60° 30′ N.,[364] the equivalent of a latitudinal displacement of 2000 km. The glacial isochional lines for west Bosnia and Herzegovina are in agreement.[365] The isotherms moved through 13–15° of longitude[366]; France was deeply influenced as is shown by the loess deposits and by the absence to-day of true cave-forms from the west of the country north of the Garonne[367]; and south-west Ireland had the climate of north-west Iceland, the western part of the Iberian Peninsula that of north Greenland. The cold front in winter skirted the west coast of Europe from Tromsö to Brittany.[368]

The Pleistocene climate had the same harmony as to-day only a few octaves lower.[369] The world's climatic zones outside the regions affected by the ice-sheets persisted almost undisturbed. Tropical glaciers in equatorial Africa

and South America, though larger than their successors, had the same orientation.[370] The present conditions were merely accentuated[371] in west Europe, Black Forest, Tatra, Balkan and Iberian peninsulas, Caucasus, Asia Minor, Persia, Andes, western United States, British Columbia and Alaska. The difference between the northern and southern sides of the Pyrenees and Alps, and between Switzerland and the Tyrol and Austrian Alps, was just as noticeable,[372] and precipitation, as now, increased northwards in the Apennines.[373] The British Isles, with their low snowline and heavy precipitation, lay within the influence of the Gulf Stream,[374] as did Norway—this is suggested by the ice-free strips in the coastal areas[375]; winds blowing in the same direction as now fed the ice of the Altai[376]; the warm Gulf of Mexico, with its strong evaporation, nourished the North American ice-sheet (see p. 671); and deficient precipitation caused northernmost Greenland[377] and the northern Rocky Mountains[378] to be bare of ice as at present.

The southern limit of the ice-sheets in Europe and North America coincided with the mean annual isotherm of 12·8°C of to-day, and the course of the boundary of the ice in the U.S.A. brings out the resemblance between the Pleistocene and present climates (see p. 641). The most southerly local glaciers in North America were shifted from 37° 35′ N. (Blanca Peak[379]) to 34° 14′ N. (see p. 731).

The snowline in the southern hemisphere, which to-day for antipodal and climatically similar places is 300 m lower than in the northern hemisphere (see p. 167), betrayed a like relationship[380] though the more or less permanent Antarctic glaciation tended to stabilise the climate of its hemisphere. The existing pressure distribution was intensified without appreciably altering the distribution itself. Asia, like north-east Australia, probably had a monsoon climate, though a weaker one, since inblowing winds were light and in places did not exist. Its anticyclone, which was possibly less strong during the interglacial epochs but much stronger during the glacial epochs[381]—the semi-arid region north of China shifted south by about 4° Lat.[382]—was probably moved slightly southwards[383] and may have coalesced with that of north-west Europe[384] (see below). The two major pluvial phases in south-west Arabia, each divisible into at least two subphases, may have been caused by a displacement of the monsoon zone[385] which in the Horn of Africa was stronger (see p. 1138). The south-east monsoon was the rain-bearer in glacial Kuen-lun.[386]

The ice-sheets and their glacial anticyclones made the temperate latitudes colder in the northern than in the southern hemisphere. Together with the cause which induced glaciation, they compelled the subtropical belts of high pressure to approach the geographical equator (see p. 1137) and the thermal equator to move in the same direction.[387] The movements of the latter may have been an important cause of climatic fluctuations in the tropics[388] (see p. 1138).

3. *Glacial Anticyclones and Nourishment of Ice-sheets*

Present anticyclones. The main departure from the present climates was in the accumulation of cold and heavy air, the glacial anticyclones, which overlay the ice-sheets more or less permanently as they do now. The anticyclone above the present Greenland was proved for the south by Mohn and Nansen[389] and for the north by Peary.[390] Fricker's suspicion[391] that one existed over the Antarctic was confirmed by expeditions at the beginning of

the 20th century[392]; it explains the more or less homogeneous climate in the Antarctic in striking contrast to the climatic variations of the North Polar regions. These modern anticyclones, which have large temperature amplitudes on clear days,[393] are demonstrated by the centrifugal winds. Encountered by all trans-Greenland expeditions and induced by gravity and by temperature inversions,[394] these winds blow often with great violence, as in the Antarctic blizzards, and with impenetrable and opaque snow storms. They extend as far as 200 miles (*c.* 320 km) outside the ice-margin[395]—in the Antarctic the surface is swept bare in numerous places[396]—and are strengthened by the low-pressure systems over the Ross and Weddell Seas[397] and off the coast of Greenland[398] where "fjord-gales" occur and foehn winds roar like a train down the main fjords.[399] They are facilitated by the lightness of the snow in high latitudes and by the very low friction with the smooth surface of the snow which is less than that of the sea.[400] They sweep the snow from centre to periphery, as Peary[401] first noticed and Hobbs[402] expressed in his term, the "centrifugal broom". The amount so swept has, however, rarely been estimated and then only very roughly[403] because of the wide variations and rapid changes in drifting conditions and the impossibility of distinguishing between wind-drifted and newly fallen snow. In Adélie Land at least 50 tons of snow are carried from the ice-sheet across each metre of the coast-line during a day of heavy blizzards,[404] and the quantity shifted annually by the wind on the Isaachsen Plateau of Spitsbergen may be *c.* 9 million cu. m.[405] In Dronning Maud Land the amount so removed is not large (Swithinbank, 1955).

The anticyclones are demonstrated too by the westerly drift of the Antarctic pack-ice, as noted by the *Belgica*, *Gauss*, *Endurance*, *Aurora* and *Deutschland* expeditions and displayed in the drift of the *Gauss*[406] (1902) and in the tracks of the *Deutschland*[407] (1912) and *Endurance*[408] (1915) in the Weddell Sea. Here, the drift is thrice as quick as in the North Polar basin[409] and the cyclone presses the drift-ice against the west side of the bay, making this inaccessible. Near the Antarctic continent, there is a narrow zone in which the surface-current flows westwards. Where this reaches eastern Graham Land, it is turned northwards into the belt of westerly winds (see p. 193) and leads the pack-ice and bergs of Weddell Sea north-eastwards to Bouvet Island. This explains why the Antarctic Convergence (see p. 1094) is farthest from the Antarctic in this region (50° S. as against 60° S. elsewhere) and why Weddell Sea is the main source of the bottom waters.[410] The boundary between the East and West Wind-drift in the Antarctic Ocean is shown in the text-figure (fig. 117).

The autocirculation is further confirmed by the calms or variable light winds in the centres of the ice-sheets,[411] both in Greenland and in the Antarctic where the snow-surface is quite soft and the sastrugi are few and inconstant—they do however occur at the South Pole. Return air-currents at high levels, as portrayed by the cirri, e.g. in Greenland,[412] and by the cloud banner and smoke on Mount Erebus[413] (4054 m), are additional proof. Kites, pilot-balloons and recording anemoscopes show that in both east and west Greenland outflowing winds are ousted by incoming currents[414] at heights of 750–5000 m and in the autumn even up to 7000–9000 m, and that easterly winds in the Antarctic reach the ceiling of the troposphere, but give way to south-west winds above 9000 m[415]—the tropopause disappears during the Antarctic winter. The upper air-currents in Greenland have been interpreted

as not symmetrical about the ice but as a continuous west–east movement.[416]

The Antarctic's atmospheric circulation and its causes and effects are still only imperfectly known. The meteorological data are available for only a score or so isolated localities on the periphery of the continent and almost at sea-level: observations have been made up to the present (1953) for one or more years at about fifteen places on the margin, on three ice-bound ships drifting slowly, and for four subantarctic islands. Of the climatology of the interior nothing is known for the southern winter half-year (March–Septem-

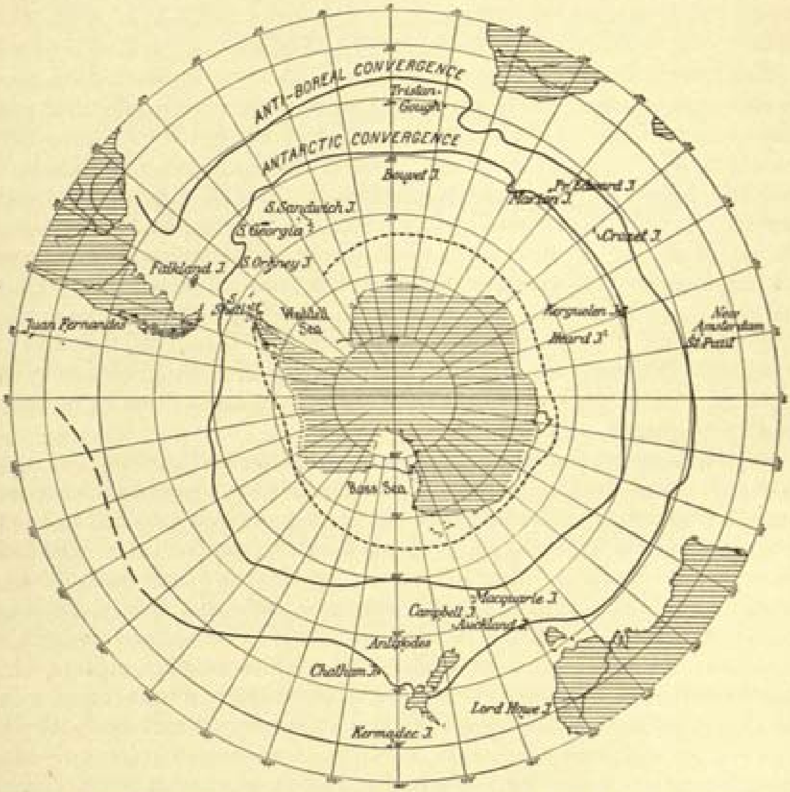

FIG. 117.—Boundary between east and west wind-drifts in the Antarctic (dash-line), with the Antarctic and Subantarctic (anti-boreal) convergences. G. E. R. Deacon, *CR. C. Gg.* II (iib), 1938, p. 7.

ber) and no spot during the Antarctic summer has been occupied for more than one week.

The extent, depth and permanence of the Antarctic anticyclone are matters of debate among meteorologists (see p. 662). Some meteorologists (see p. 663) place the anticyclone only around the edge of the continent (W. Meinardus, G. C. Simpson) while others extend it as a thin layer (E. Barkow, E. Kidson, G. Grimmeyer) or as a major feature (W. H. Hobbs) or break it up into several lobes or cells (H. H. Lamb), especially at low-index periods and in the "south-east corners" of the three oceans washing Antarctica. It is probably eccentric towards the Indian Ocean[417] and wedge-like over Graham Land,[418] giving south-west winds with cold air on the east side and north-east winds with warm air on the west side of this land.

It fluctuates with the season,[419] especially in the region of Ross Sea, and as A. Supan[420] surmised wanders eastwards in winter and westwards in summer[421] at which season it also contracts.[422] It may be a recurring feature.[423] The pressure falls almost imperceptibly from the anticyclonic centre to the permanent low-pressure systems controlled by the higher temperatures and low altitudes of Ross and Weddell Seas[424] and the Southern Ocean between 50° and 65° S. Lat. where it is bounded on the north by the 740-mm isobar at sea-level. The fluctuations of the polar front along this line explain the varied weather, especially of the many polar stations which have been situated along the continental margin.

These glacial anticyclones are secured by the high altitudes of the land and are connected, as laboratory experiments confirm,[425] with the snow's low thermal capacity and conductivity and high reflecting power, snow being an almost perfect reflector for short waves and practically a full radiator of long waves.[426] This induces great cold. In Greenland, the marginal zones are about 0 °C and the fairly well defined "central cold region",[427] first recognised by A. de Quervain (1912), mapped by J. P. Koch (1930) and W. H. Hobbs (1944) and characterised by low wind velocity, fine dry snow, and fogs, mists and halos, is commonly −32°C[428] and exceptionally at Wegener's *Eismitte*[429] (the coldest place, both in the extreme and mean values, on the earth's surface) −86°C, with an annual mean of −32·5°C. In the Antarctic, high altitude and latitude combined with the high albedo (especially in summer) produce the extremely low temperatures,[430] such as −58·5°C observed by Amundsen, −60·6°C by Scott, and −60·5°C by Byrd on Ross Barrier and a mean winter temperature in the high interior of −56·7°C. While the temperatures decrease in winter towards the pole,[431] the region about the South Pole must be one of the coldest places on the earth,[432] though the "cold pole" of the Antarctic may be in Neu-Schwabenland,[433] whose highest point is in 81° S. Lat. 0° Long. At the fringe, where the greatest contrast in temperature between land and sea favours cold winds, low temperatures have been recorded,[434] e.g. −41·7°C (mean, −13·9°C) at Cape Adare, −43·3°C (mean, −11·8°C) in West Antarctica, and −41·0°C at Kaiser Wilhelm II Land; the low-lying Ross Barrier is probably a sink for some of this cold air—the mean temperature in the middle of the shelf-ice is −32°C—though the area is invaded by strong flows of warm air from the north and north-east.[435] The mean April–October temperatures (southern winter) recorded were Snow Hill −17·9°C; Gaussberg −17·5°C; Cape Adare −21·4°C; Ross Island −24·5°C; and Framheim −36·0°C. Full tables[436] of monthly mean temperatures with annual temperature curves of the various polar regions bring out very clearly the influence of the ice-sheets.

The meridional temperature gradients between 50° and 90° S. Lat. have in all latitudes the smallest values in summer (minimum in January), the highest in winter (maximum in July or August), viz. more than 1°C for every degree of latitude. The greatest differences at all seasons are between 70° and 80° S., i.e. at the transition near the edge of the ice-sheet, and are especially great between these latitudes in March and April when the subantarctic waters are warmest. In January, the isotherm of 0°C runs roughly along the margin of the continent and encloses 26 million sq. km while in the winter it encloses roughly twice that area[437] (51 sq. km).

Glacial anticyclones invert the temperatures[438] as Fricker[439] predicted in 1893, though the draining away of the cold air by down-slope winds prevents

the inversion air from becoming too thick. Clear skies, small humidity, and rapid radiation from the ice give alternations of inversions in the Antarctic, as in the Ross and Weddell regions, of up to 1000–1500 m, the upward rise being not uncommonly 10°C and occasionally 19·5°C.[440] The inversions explain the most unusual visibility which has led to such curious errors in Antarctic mapping[441] and astonishing underestimates of distance. The temperature-inversion, which is fairly stable, is associated with winds whose velocity diminishes upwards and into summer and along the flatter stretches,[442] as over the centre of Ross Barrier.

The ice in the Arctic Ocean tends to produce an anticyclone and spread Arctic conditions in a broad zone about its margins. Nevertheless, a permanent high pressure system does not exist, for cyclones, often intense, penetrate the region, especially during the cold period of the year. In summer, they accelerate the break-up and movements of the ice.

Pleistocene anticyclones. Tutkowski postulated a permanent anticyclone over the Scandinavian ice to account for the loess (see p. 530)—A. G. Nathorst[443] had already suggested an east wind. This view (occasionally denied[444]) was developed climatically by Harmer[445] and Meinardus[446] and has now become a glacial doctrine.[447] Analogy with modern glacial anticyclones makes it reasonable. Nevertheless, unimpeachable geological evidence is singularly meagre. The distribution and origin of the wind-blown loess (ch. XXVI); asymmetrical meridional valleys in Galicia[448]; the orientation of the Carpathian glaciers[449]; the drift of floating ice and its erratics along the south coast of England[450]; the wind-blown sand on slopes facing east above the infraglacial raised beach of Gower, south Wales[451]; the westerly carry by the wind of charcoal from palaeolithic fires, e.g. at Willendorf[452]—each of these has been cited in support.

Although an anticyclone most likely existed over the European ice creating easterly or north-easterly winds in summer and south-easterly winds in winter,[453] its influence probably ceased but a short distance beyond the ice-margin. This agrees with evidence from modern ice-sheets,[454] as H. Rink first noticed, and with numerous observations from glacial Europe. The very glaciation of this continent is only possible with such moisture-bearing winds[455]: the Atlantic, as now, was the giver of the precipitation: southerly winds from the Bay of Biscay may have blown over the British Isles.[456] The snowline rose eastwards in Europe (see p. 651) and was comparatively low on the northern flanks of the Pyrenees[457] and in the British Isles (see p. 651); the cirques were disposed on eastern and northern slopes (see p. 297) from the Lofoten Islands[458] to Albania[459] whose snowline rose where high mountains stood in the path of the westerly winds and fell where wide gaps gave access[460]; the *galets exotiques* drifted eastwards up the English Channel[461] (see p. 1097). The distribution of the ice in Steiermark,[462] Iberian Peninsula,[463] southern Carpathians[464] and the Alps[465] (see p. 715)—it is not feasible to explain this by east winds, as Walther[466] tried to do—and that of the "periglacial dunes",[467] the dunes of Gascony (see p. 1358) and the pumice tuffs of the Laacher See volcanoes (see fig. 106, p. 534) also prove westerly winds south of the ice-sheet (cf. p. 532). Westerly winds blew all the year round over the Pyrenees[468] and over Europe's southern peninsulas,[469] which probably had rain at all seasons (see ch. XL) and were forested (see p. 1379) as in modern Patagonia, Alaska and New Zealand, as well as over Corsica[470] and coastal Algeria and Tunisia where their character and direction

did not differ appreciably from the present.[471] These westerly winds fed the glaciers of the Apennines, Balkans, Caucasus, Asia Minor and Turkestan.

The anticyclone was probably shallow along the ice-edge so that cold and dry north-east winds underlay moist south-west winds. Western cyclones with cumulus clouds had access to the corridor between the Scandinavian and Alpine ice-masses,[472] except in winter when it was under snow and the winds were reversed (see p. 534). Above the inversion layer west winds replenished the ice. The southern limit of the loess in north Germany may give the boundary between dry east winds and warm moist winds[473]; it fixes the width of the extraglacial belt, subject to anticyclonic winds, at *c.* 100 km,[474] though this figure has been raised to 700 miles (*c.* 1120 km) in central Europe and to 400 miles (*c.* 640 km) in North America.[475]

North American conditions were indeed similar (cf. p. 533). East winds may have swept across the front of the ice-sheet, as the orientation of the pahas (W.N.W.–E.S.E.) of Iowa (see p. 519) and of the glaciers attest,[476] e.g. in north Washington, Idaho, Montana and Utah, though the channels cut by glacial melt-waters in western North Dakota and Montana show that even here the plains were less dry and characterised by storminess and overcast skies.[477] Farther south, east winds yielded to west winds. In the Great Basin, they generated asymmetrical volcanic craters,[478] threw up big beaches on Lake Bonneville's eastern shore[479] and developed glaciers,[480] mostly on the western sides, in the Uinta Mountains of Colorado, in the Sierra Nevadas and Bighorn Mountains and in New Mexico.

The very marked line between the ice and the periglacial region beyond created a steep temperature gradient and favoured a much more pronounced polar front with greater stability and extension.[481] Hence cyclones travelled along the front and caused changes of circulation more widespread than now. The conditions in summer resembled those of present winters as regards the dependence of the temperature upon circulation.

In both the Old and New Worlds there undoubtedly existed seasonal fluctuations of pressure and other distributions, and even fluctuations of shorter intervals.[482] The storm tracks swung polewards to the edge of the ice-sheets or over their peripheral parts and so contributed more to the nourishment of the ice than did the winter storms which were only responsible for the pluvial conditions of lower latitudes.

Nourishment of ice-sheets. Previous to the expeditions to Greenland and Antarctica and their evidence that anticyclones cover the ice-sheets, it was assumed, as by Maury, that the low pressures of the higher middle latitudes prevailed in still higher latitudes and on the great ice-fields. Only so, it was thought, could ample precipitation be provided to replenish these ice-masses. By disproving this assumption, the manner in which the vast ice-sheets are nourished has been left obscure. Some writers indeed deny them permanent stationary anticyclones[483]: H. H. Lamb states that this is true of the present Antarctic which has cyclones over Ross and Weddell Seas, westerly winds which blow along the coast and the cloud types which include extensive upgliding frontal types. They also contend that alimentation under anticyclonic conditions is impossible[484]—the stable conditions and low temperature and low vapour content of the air are inimical. Others affirmed that the Antarctic ice was possibly discontinuous within its circumscribing belt[485] or that central Greenland had only thin ice[486] or was ice-free, with a luxuriant vegetation[487]—the Eskimos thought supernatural animals inhabited

it, and a military expedition, with field guns, was sent to subjugate the peoples supposed to reside there.[488] According to others, the Antarctic ice continues to draw upon its Pleistocene resources and by its present retreat is approaching the equilibrium the existing climate demands.[489]

Nourishment, however, even in the centre of the ice is fairly heavy: at the *Eismitte*[490] (70° 54′ N.; 40° 42′ W.), the annual increase amounted to 31·4 cm of water, snow fell on not less than 55 % of the days in the year, and the cloudiness averaged nearly six-tenths. In other places in Greenland, the precipitation has amounted to 35 cm of water[491] and at the Ice-cap Station of H. G. Watkins (67° 3′ N.; 41° 49′ W.) was considerable and heavy at times[492] (but was not measured continuously). That it is very considerable is proved by the fact that notwithstanding the great loss by calving (see p. 185) the Greenland ice-sheet is practically in equilibrium.[493]

Both precipitation and wastage are slight in the Antarctic, the loss being largely produced by calving. In Graham Land, shrinkage is by ablation, in Ross Sea region by starvation.

Nourishment probably takes place by upslope cyclones,[494] made possible by the displacement of the anticyclone,[495] due possibly to atmospheric variations over the whole globe.[496] While practically all the cyclones of Greenland move along either the east or the west coast of the country,[497] i.e. along either Davis or Denmark Strait, some approaching from the west challenge the strength of the anticyclone and cross the narrower part of Greenland between 60° and 66° N. as Mohn[498] first suspected, and through the gap between the two major ice-centres[499] (see p. 75) where the physical barrier is lowest. Cyclones also enter occasionally from the east and, like those from the west, appear generally to withdraw again to the side from which they had come.[500] Deeper and higher cyclones apparently very occasionally traverse the wide central as well as the narrow southern Greenland,[501] generating a "total foehn", i.e. a continuous barometric gradient and air current from coast to coast, and the clouds, including warm-front types, that are never quite absent during a transectional expedition. The summer pressure in the interior is as variable as at the coast[502] and observations at Wegener's and Watkin's inland-ice stations show that warmer masses of air, which raise the temperature by as much as 40° or even 50°C and sweep away the cold air skin (*Kaltlufthaut*), flow over these parts, often with a high velocity and with a complete change of wind direction, so that the "central cold region" (see p. 659) which is only 300–500 m deep[503] is impermanent.[504] One such "low" passed the west on 23 March, 1931, at 4 p.m., crossed the *Eismitte* on 24 March at noon and reached the east on 25 March at 4 a.m.[505] It has, however, been suggested that these disturbances are not sea-level pressure systems, which could not cross such high barriers, but higher-level perturbations that overlie the surface cyclones.[506] The seasonal distribution of precipitation and synoptic meteorology prove that the anticyclone is most disturbed in autumn and early winter.[507] At *Eismitte* heavy snowfall generally coincided with a rise of temperature[508] (*c.* 6°C).

The north winds encountered by Amundsen in 88° S. Lat. and the observations by the whaling-ship *Balaena* may indicate that cyclones and snow-bearing winds also penetrate the heart of the Antarctic.[509]

Meinardus,[510] in a view which has strong approval,[511] maintains that the centre of the Antarctic plateau pierces the polar cyclone which on Ferrel-Hildebrandsson's theory overlies the anticyclone; that the latter has an

oscillatory base and a centre towards the Atlantic Ocean and so is influenced by westerly, moisture-bearing winds—blizzards have been encountered on the plateau. The anticyclone is shallow, not more than 2,000 m high, and confined to a narrow fringe. In central Greenland too it is probably limited to a layer near the surface and below the mean cloud height; pilot balloons at the *Eismitte* suggest its depth does not exceed 500 m.[512] Hence, the ice-sheet is fed by winds that stream at high levels, either radially and symmetrically inwards from the margins, as Hobbs and Wegener suggest, or eastwards steadily across it.[513]

Other meteorologists[514] deny that the Antarctic continent anywhere pierces the anticyclone: the extreme cold and outflowing winds on the central plateau,

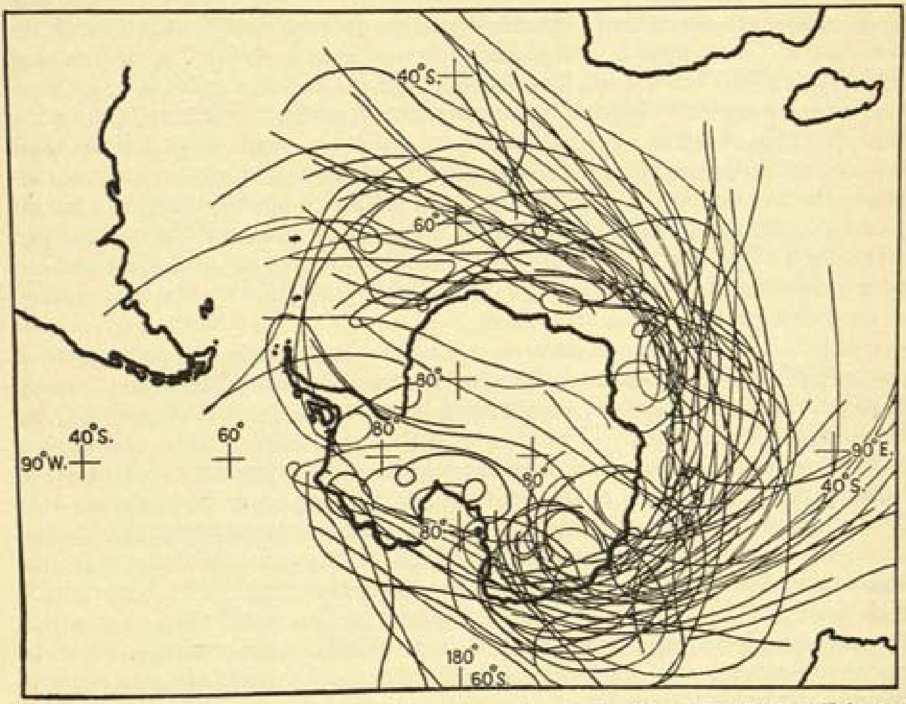

FIG. 118.—Depression tracks over the Antarctic continent and adjacent seas from 22 February to 5 April, 1947 (42 days). Chart incomplete in Pacific sector between approximately 180° and 50° W. and everywhere north of 40° S. H. H. Lamb, *A. int. Hydr. Sc.* 1951, I, p. 182.

the known pressure distribution, the northerly movements of the clouds, and kite observations at the margins disprove this. They estimate the anticyclone's height and the base of the "snow-supplying cyclone" above the plateau at 1000 m and an even higher absolute figure at the margin. The greater part of the continent may be immune from travelling cyclones,[515] though depression tracks do sometimes cross the continent[516] (fig. 118). They probably fill up rapidly as they leave open water and lose energy.

Hobbs's view. Hobbs,[517] though generally agreeing with the view expressed above, has formulated a slightly divergent hypothesis. The circulation, he contends, is only anticyclonic if the cold surface is domed. Air, chilled by radiation and contact with cold or snow, slides outwards down the physical declivities under the influence of gravity with an accelerating velocity.

The flow is not steady but in thermodynamic "strophs" or "pulses" which manifest themselves in alternating calms and blizzards. These are caused by progressive adiabatic warming (by compression) of the air during its descent to the ice, the flow along the surface gradually damping and finally stopping the air-flow so that calm ensues. The cool air once more becomes denser and acquires the steady acceleration velocity of bodies sliding on inclined planes. Blizzards are followed by a rapid rise of temperature, a fall of snow and another calm. The strophs synchronise with the passage of a cyclone along the coast[518] which "sucks out" the air, and are related in Greenland to the North Atlantic cyclones[519] and in the Antarctic to storms on the south Australian coast.[520] Hobbs illustrated the mechanics of the glacial anticyclones experimentally.[521]

Although the anticyclone extends up to the tropopause[522]—the indraft, in the case of Greenland, is noticeable as far away as Iceland, Jan Mayen and Spitsbergen[523]—Hobbs ascribes the snowfall to the ice-needles of the cirrus and cirro-stratus which with stratus clouds are generally recorded above the ice.[524] The needles are adiabatically melted and vaporised during their descent and are precipitated as fine needles and snow as they melt the cold air above the ice; hence, the overcast skies and falling ice-spicules of the Antarctic plateau and the relatively high humidity, mists and frequent "frost snow" of Greenland's interior.[525] In his opinion, the cyclones penetrate Greenland over only about 100 miles (*c.* 160 km), and then only in summer, and instead of nourishing the ice cause its melting.

Hobbs's view seems erroneous[526]; for the ice-sheets are probably not nourished by such radiation and the outflowing winds are katabatic ("down-flowing") and independent of pressure: doming may result from and not cause glacial anticyclones[527] which are unable to develop in spite of the great cold because of the constant drainage winds. The view fails to take sufficiently into account the small quantity of moisture over the interior—the Antarctic ice-sheet which better exemplifies Hobbs's theory than the Greenland ice-sheet is seemingly starved (see p. 461)—the strength of the marginal winds, and the adiabatic warming of the descending air. The surprisingly high degree of cloudiness and its nature in central Greenland point to nourishment from clouds and from rising air associated with cyclones.[528] The centres of elevation ("domes") on the Greenland ice-sheet are also more in keeping with this theory.[529]

Simpson's view. Simpson[530] who places a vast cyclone over the elevated plateau and an anticyclone over the other half of the Antarctic which is at or near sea-level, explains the bad weather around the continental margin, not by a cyclonic procession, as some believe,[531] but by deep and regular pressure waves which, accepted by others,[532] proceed outwards from the anticyclone's centre, with wave-fronts parallel with the coasts. These surges, which force the chilled air to ascend and induce precipitation, are traceable as far north as Kerguelen. They cause blizzards if the pressure-curve is rising and calms and northerly winds when it is falling. The relatively warm air of the blizzards is attributable to temperature inversions and not to foehns; for the cold air of the inverted layer is replaced by the warmer air from above and the abnormally cold air of the calms between the blizzards is swept away and the normal temperature is restored.

Strong radiation cools the air abnormally, especially immediately above the ice. The heavy air raises the pressure towards the interior. The cyclone

above the anticyclone, which is formed by the relatively rapid changes of vertical pressure induced by the cold, dense air, conveys air over the polar region from lower latitudes to supply the anticyclone's outblowing winds with moisture. This circulation is normally slow and the air warms dynamically, so dissolving cloud and producing cooling and temperature inversion. Imposed upon those normal fine-weather conditions, which in the Antarctic occur especially during the summer months, are the pressure-waves which travel more or less quickly outwards from the centre, altering the distribution of surface-pressure and introducing an air-motion which is commonly accompanied by forced ascending currents. These compel the cold surface air to rise and cool rapidly and precipitate its water-content in the typical Antarctic blizzard. Even after descending from the upper atmosphere, this air is in such a state that a forced descent of a moderate amount brings about condensation. While Simpson's pressure surges have been accepted by some meteorologists,[533] by other meteorologists they are thought merely to reflect the passage of ordinary fronts and depressions.[534]

These divergent views about the way in which ice-sheets are fed show how much uncertainty still surrounds this important question. Precipitation seemingly takes place in several ways, viz. at the margins[535] by adiabatic cooling, by mixing air-bodies of different temperatures, by warm air making contact with cold ice and by outside winds coming in; and in the interior[536] by moisture brought in from lower latitudes by cyclones which overlie or cross the elevated region.

Marginal nourishment. The annual amount of precipitation in the heart of the Antarctic is unknown and may be almost balanced by ablation[537]; at the South Pole it may be as little as 5 mm,[538] though it has been estimated to be 2 cm[539] (ablation 1 cm) or less than 5 cm.[540] The annual growth in the interior of Greenland[541] is possibly equivalent to 30 cm of water or between 33·6 or 36·2 cm, or a total precipitation of *c* 40 cm after the loss by ablation (calculated from Westmann's formula) is allowed for: this is roughly the figure given by the rate of discharge of Greenland's bergs.[542]

The annual marginal precipitation,[543] though much heavier, is nevertheless small, as it is in polar regions generally. Actual measurement proves this, as do the snow and ice-free areas and the dead ice denoting starvation.[544] In west Greenland,[545] it is of the order of 1 m and decreases rapidly northwards: this is shown by the constant height of the snowline (*c.* 1400 m) in spite of the northerly fall of temperature. In the Weddell Sea area, it is 96·52 mm of water and on Ross Barrier 190 cm of water[546]; other estimates for various years[547] were: Cape Evans 41 cm, Cape Royds 23 cm, Cape Adair 36 cm; Gauss station 80 cm, Maudheim 150 cm, Charcot's Graham Land bases 34 cm and 38 cm, and at the *Deutschland* base 11 cm. The figure for the whole Antarctic coast may range between 10 cm and 43 cm.[548] Variations are considerable; the precipitation is small on Gaussberg and on Adélie Land which have much ablation, is somewhat heavier on the lower reaches of the outlet glaciers of the Ross Sea quadrant, and is relatively high[549] on the pack-ice and on O. Nordenskiöld's ice-terrace and other shelf and piedmont masses which grow chiefly from local snowfall. On the coast of Antarctica this extends to the neighbourhood of the Antarctic Circle—dense stratus and cumulo-nimbus clouds accompanied by heavy falls of snow periodically extend inland for over 100 miles (*c.* 160 km)—and is due to the passage of frontal movements associated with the Southern Ocean cyclones and with

Simpson's pressure waves (see above). On Ross Barrier, the net accumulation in regions 100 miles (*c.* 160 km) or more from open water is only a small percentage of that occurring within 50 miles (*c.* 80 km) or less of open water.[550]

From recent observations it seems clear that the ice-flow on the plateau, on Ross Barrier and in practically all glaciers is considerable, and that the precipitation far exceeds that removed by ablation and by wind-drift and suffices at least to balance the depletion caused by flow.[551] Stagnant glaciers, such as the very sheltered Taylor Glacier and the Koettlitz Glacier which has a very limited drainage basin, are exceptional.

The precipitation increases northwards. Glaciers on the east coast of South Victoria Land become progressively more active to the north[552] and glaciation increases in this direction from the Cape Adare region[553] to apparently (for this is contested[554]) a zone north of the Antarctic coast,[555] passing through Bouvet, the islands in Gerlache Strait and off Graham Land, and the intensely glacierised Balleny Islands. The marginal precipitation occurs orographically, by air-mass instability, from frontal cloud masses and in cyclonic situations.

Antarctic ice grows in summer when the belt of sea-ice is narrowest, the air is warmest, the snowfall heaviest and the winds least strong.[556] All expeditions[557] have stressed the violent winter winds and the restriction of growth to summer. In Graham Land,[558] the winter half-year showed a decrease of 2 cm and the summer half-year an increase of 25–30 cm. The fine snows (*chasse neige*), which drift with the slightest wind and frequently fill the air, lodge in fissures or in the lee of rocks or of projections like Gaussberg.[559] They build snow-borders or fringing or cliff glaciers in both Greenland and Antarctica (see p. 90). Much is blown out to sea, especially on the western sides of Weddell and Ross seas, whose temperatures it lowers appreciably[560] (see below).

Early writers[561] were of the opinion that precipitation was not restricted to the interior but nourished the whole ice-sheet. Later, the importance of marginal snowfall during the Pleistocene was emphasised[562] (see p. 124). This snow may have generated secondary ice-centres[563] or produced low-ice-domes[564] which shifted and so caused the variations in ice-flow which have been interpreted as "ice-centres". The snow came from the centrifugal broom and from cyclonic winds, aided by steepened temperature and barometric gradients (see below). It was plentiful if the margin faced the sea,[565] as in the British Isles, Lofoten Islands and the North American Cordillera. In west Greenland to-day the zone of maximum precipitation occurs at about 2500 m A.S.L. and about 120 miles (*c.* 190 km) from the ice-edge[566] (see p. 654).

The ice-sheets, extended by the centrifugal broom and the lifting above the snowline, brought wide tracts into the zone of nourishment so that the firn and ice developed on a far bigger scale than the relief alone justified. This elevation of the surface and its attendant changes accompanied the ice-sheet's normal growth, especially if the ice-flow was impeded in congested tributary valleys, at the mutual hemmings of flow,[567] or by barriers standing across the line of advance, as in Patagonia.[568] Within the Alpine glaciation,[569] the Jura Mountains for example carried most of the surface of the Helvetian ice above the snowline. The low gradient of the trunk valleys compelled a vast surface to pass almost simultaneously into the firn. This resulted in very large and rapid advances with virtually no further climatic

change[570] and in a quick retiral or disappearance of the ice at the dissolution.[571] It may explain the marked difference between the third (Riss) and fourth (Würm) glaciations on the Swiss Plain.[572]

Limits to growth of ice-sheets. Ice-sheets are limited by several means. Oceans stop their progress through calving and melting, as off Pleistocene Europe and south-east Labrador; semi-arid plains, with their light precipitation, clear skies, dry air and absorptive dust, cause them to halt—the advancing Keewatin ice may have been held up in this way in the lee of the Rocky Mountains,[573] and the northerly swing of the ice-edge in North America in 89–96° W. Long. and in Europe in 30–45° E. Long. may have been connected with the same factor,[574] though but for the influence of the Gulf of Mexico and the Mediterranean the swing would probably have taken place nearer to the Atlantic. Unfavourable topography also arrests them, e.g. the German Mittelgebirge in Europe and the Appalachian Mountains which conspicuously indented the ice-margin in Pennsylvania.

The ice itself imposes limits of a purely meteorological nature. While an anticyclonic circulation enables the ice to grow outwards to great dimensions, as illustrated in the expansion from Scandinavia to Britain,[575] the anticyclone automatically starves it and brings about its recession or even, as some assert, its extinction.[576] Growth is restricted by the increased size which hinders the incoming of cyclones, and by the higher reflecting power which lowers the temperature and thereby deprives the ice-sheet of moisture. A. v. Humboldt[577] early expressed the opinion that raising the surface above the cloud line limited the thickness of an ice-mass. Wastage is induced by expanding the ice radially and by the centrifugal winds which to-day in the Antarctic load vast quantities of snow on to the sea where it produces a wide girdle of solid floe. The broom acted very powerfully in curbing upward growth and may have equalled the combined effects of evaporation, subglacial melting and glacial discharge.[578]

Brooks,[579] attempting to discover the limit, found the critical radius was *c.* 100 miles (*c.* 160 km) for an ice-sheet on a conical continent with surface slope of 1 in 1000. Once this radius was exceeded the growth was rapid up to a radius of 250 or 500 miles (400–800 km), since the cooling produced by the ice was proportional to the square of the radius, but became slow beyond this. Many of the factors involved in this calculation are not amenable to precise evaluation and the results are to be regarded as a qualitative generalisation rather than as a quantitative law.

4. *Ice-sheds and Ice-centres*

Eccentric ice-sheds. The ice-sheds of the bigger masses are almost invariably eccentric; this has been established for Greenland[580] by the various transections and for the Antarctic[581] whose ice-divide may be near the Royal Society Range, possibly 100–150 miles (160–240 km) distant. The Alps had a similar eccentricity, as is proved by striae, rock-basins on cols, and by the transfluence of passes[582] from north to south, e.g. Grimsel, Gotthard, Maloja, Bernina, Simplon and Brenner, and of the passes into the Oetztal Alps. Thus the Engadine ice crossed the Bernina and Maloja passes into the big Adda Glacier and by the Como and Lugano valleys into the Plain of Lombardy.

The ice was also eccentric on Bear Island[583] (the centre lay not on Mount

Misery but on the plain), in Novaya Zemlya,[584] Pyrenees[585] and central Himalayas[586] (erratics travelled southwards over the passes from an axis 1–15 km eccentric), Peru and Patagonia,[587] and in North America,[588] as in the Selkirk Range and north of the present watershed in Labrador.

The parting in the Scottish Highlands was east of the main watershed[589]; boulders of Lewisian gneiss from the Ben More range moved westwards in Sutherland, augen-gneiss from the Conon basin was transported to Loch Broom, and granulitic Moine schist about Loch Maree was lifted to higher levels on the Torridonian and on the Cambrian quartzites. Galloway, North Wales, Co. Galway and Co. Donegal supply additional instances in the British Isles.[590]

Scandinavia[591] provides the classic example of an eccentric axis, the *Isalp* of O. Torell.[592] Discovered by Hörbye[593] in 1857, it lay 130–140 km east of the present parting in central Jämtland,[594] at 150 m in Norrland and at a distance of 200 km where the mountains were least continuous.[595] At some period, it was possibly farther east[596] over the Kola Peninsula and Gulf of Bothnia. Its zone of uncertain ice-movement—roches moutonnées, for example, are glaciated from opposite directions[597]—approached the watershed towards the southern end of the peninsula; south Norway had little or no eccentricity.[598] The ice flowed westwards and retroversely from an axis situated 300–600 m below the level of the principal divide against a gradient, as in Jämtland, of 1 in 200[599] (omitting the augmentation from isostatic depression). It engraved striae and moulded roches moutonnées facing west, east of the main watershed, as was noticed by J. C. Hörbye, P. A. Siljeström, B. M. Keilhau and J. Durocher and later confirmed for various parts of Fennoscandia.[600] Erratics were moved against the slope, e.g. in Jämtland,[601] and even in places on to the highest summits,[602] e.g. on Åreskutan, 1420 m with an uplift of 1000 m (eastern erratics[603] occur at 1800 m in Torne Träsk and at 1850 m in the Sareks region). The eccentric ice mixed erratics from east and west in the strip between the watershed and iceshed.[604] It glaciated the summits that project above the *Fjeld* and swept through the cols and gaps in the main Scandinavian watershed (*Kjöl*), e.g. Storlien Pass (596 m) which carries the railway to Trondheim, frequently converting the cols into U-valleys (see p. 332). During the retreat, it imprisoned east of the watershed, as in Lapland and Jämtland, a suite of glacier-lakes with strandlines, osar and lateral moraines which incline towards the watershed (see p. 470).

Common to all these eccentric icesheds, save possibly that in western North America,[605] is their occurrence on the inner or landward side of the principal partings—North America is not a real exception since the iceshed moved eastwards from the Coast Ranges and westwards from the Rocky Mountains.[606] Many reasons are assigned for this. In modern Greenland, for example, it is thought to reflect the asymmetry of the subglacial relief,[607] the glaciation having begun on the raised eastern edge of the country.[608] Alternatively, postglacial streams have displaced the watersheds[609] in Scandinavia, the Himalayas and Antarctica. But this is unjustified[610]; such forces as a rule have accomplished very little (see p. 508).

The eccentricity was more probably morphological.[611] The ice-divide was situated where the resistance to movement on either side was equal. There was freer and faster discharge on the one side and resistance to flow on the other. The resistance was either obstructing ice, namely, Timan ice in

the case of Scandinavia,[612] Scandinavian ice confronting the Scottish ice,[613] and Scottish ice in Co. Donegal, or low slopes, as east of the Coast Ranges of western North America or of the Scandinavian watershed, and reversed gradients, e.g. east and south-east of the Baltic and Gulf of Bothnia.[614] Nearness to the sea facilitated the flow (the iceshed was bent to the east where the passage through the Scandinavian mountains was easy and was turned to the west where it was difficult[615]). Changes in the ice-cover of the North Atlantic may in some measure have influenced the shifting Scandinavian iceshed during the various glacial phases.[616] Calving also was a factor[617] since it facilitated flow: where calving did not take place, viz. in the North Sea, the ice extended much farther.

Some climatic control was present, due to decreased ablation[618] or increased precipitation[619] in the east connected with the condensation associated with a glacial anticyclone[620] or with wind transport from the west,[621] east or south-east[622] (see p. 533), or possibly with the elimination of the Gulf Stream by the ice and icebergs of the Scandic[623]—the circumpolar Southern Ocean made a similar action impossible in Patagonia.[624] Cyclones, with their warmer temperatures, may also have favoured eccentricity by easing the summer flow over the lands.[625] The great expanse of the European ice-sheet to the south-east has been linked with the flow from Scandinavia and with the precipitation by westerly winds in the central European corridor[626] (see p. 532).

Hence, eccentricity had probably a complex origin: writers have merely emphasised particular facets of the problem. Unfavourable subglacial relief and opposing ice-masses on the one hand and ready discharge to the sea, with ablation, marginal melting and calving on the other, aided or modified by temperature, wind and pressure acting upon the ice-surface, have all played their part.

Evolution of Scandinavian eccentricity. The Scandinavian eccentricity may have been due to an independent growth over the Baltic[627] which pressed back the glaciers of the watershed. Much more probably, it evolved from a mountain glaciation astride the 800 miles (*c.* 1300 km) long watershed[628]; for though striae and roches moutonnées of the early phase ("proteroglacial"[629]) are rarely preserved,[630] erratics including those of the earlier drifts prove such a sequence for instance in north Fennoscandia.[631]

The maximum eccentricity is less certainly dated. Some refer it to maximum glaciation[632]—for example, it was above the Gulf of Bothnia and the Kola Peninsula at this time and preceded the lateglacial phase in the Sareks region. Others place it in the lateglacial[633] or begin it in the Daniglacial.[634] The question is partly bound up with that of the manner of the ice disappearance. According to some, the axis shifted westwards in the final stages,[635] the ice breaking up into a network of glaciers as the divergent striae and morainic arrangement appear to suggest. Yet it is more likely that the ice lay as narrow strips on the eastern slopes,[636] impounding lakes which finally drained into the Baltic by *Aftappning* (see p. 470), leaving remnants in the valleys which were either stagnant[637] or still capable of movement.[638] As far north as the Sulitelma-Sareks massif, the last ice-remnant was unquestionably eccentric[639] and out of harmony with the climate—Norrland's glacier-lakes persisted, it has been said,[640] into the postglacial climatic optimum though this was almost certainly not so. The south Scandinavian ice lay on the watershed and elsewhere only retreated on to this[641] if, in accordance with the generalisation of

E. O. Schiötz,[642] the snowline rose slowly as glacial conditions passed away. Indications in north Jämtland and Dalarne suggest that there were two ice-divides in the final stages, one due to new conditions, the other to conditions long past.[643]

Migration of ice-centres. The more or less independent ice-centres did not quite synchronise in their development, culmination or waning. Waves of glaciation passed over north-west Europe and North America.[644] The Siberian ice, increasingly deprived of moisture by the growth of pack-ice in the Arctic Ocean (which reduced the amount of moisture in the air) and by the Scandinavian ice to the west, probably shrank before the latter attained its maximum.[645] The Timan ice preceded the Scandinavian ice as the drift succession in the Kanin Peninsula testifies.[646] The Mindel glaciation in Russia was Scandinavian in origin; the Riss was influenced by the Timan-Ural confluence; and the Würm saw a return of the Scandinavian ice.[647] Lamplugh's East British Ice[648] advanced at its maximum against the flank of the receding Scandinavian ice[649] and was in turn followed by the West British or Irish Sea Ice,[650] whose shelly drifts are overlain by Ivernian drift from Loch Foyle in the north to Youghal (Co. Cork) in the south.[651]

This westerly transference of the areas of growth in north-west Europe had its North American counterpart, the centres also moving towards the North Atlantic, in this case eastwards. This view, suggested to R. Chalmers in 1890 by studies on striae, was developed by G. M. Dawson,[652] who thought the drifts and boulder-trains east of the Rocky Mountains pointed to an axial migration from the Cordillera to the Laurentian plateau, and by J. B. Tyrrell[653] who said the Cordilleran ice attained its maximum earlier than the Keewatin ice and this in turn retreated hundreds of miles before the onset of the Labradorean ice. In his opinion, each centre also shifted slightly to the south-east, as in the case of the Keewatin ice, though A. P. Low[654] detected a north-westerly movement through 350–400 miles (560–640 km) of the Labradorean ice—later writers[655] have found evidence of a shifting of the ice-divide in the later stages of the Labradorean glaciation. The Iowan glaciation has also been credited to an eastward growth.[656]

Leverett,[657] from morainic lines and overlapping till sheets in the Middle West, arrived at the contrary view, viz. that the Labrador, Patrician and Keewatin ice-centres grew progressively westwards during Illinoian and Wisconsin times—the peripheral Wisconsin drift in the Middle West was deposited by a succession of culminating ice-lobes flowing from the north-east (Labrador), north (Patrician) and north-west (Keewatin). The late Wisconsin ice overran part of the Iowan drift and of the Peorian loess, its grey drift in Minnesota overlapping red drift of the Patrician ice of the middle Wisconsin stage. Others[658] have also believed the ice east of the Rocky Mountains during the Wisconsin stage nourished by winds from the south and west, grew westwards as a Laurentide ice-sheet from valley and piedmont glaciers in the north-east of the continent—the mountains of Baffin Land (*c.* 3000 m high) and Ellesmere Island (*c.* 3300 m high), of coastal Labrador (1300–1500 m high) and of east Quebec (900 m high)—later merging with outposts in Newfoundland, Gaspé Peninsula, the highlands of New Brunswick, and the White Mountains in New Hampshire. The ice-sheets therefore were immigrant or intrusive and did not develop *in situ*. Russell[659] gave the Cordilleran ice a late date.

These divergent views may perhaps be reconciled if we conceive the

glaciation to have been eastwards in the early stages and westwards in the later ones, including the Wisconsin glaciation.[660]

A number of Polish and other geologists have also claimed[661] an easterly migration for Europe, though by no means conclusively.[662] They postulate a first glaciation in the British Isles and Norway, a second over north Germany, and a third over north Germany and Poland. M. Limanowski,[663] for example, designated the German drifts L1, L2, L3 and L4, L2 ceasing on the Rhine, L3 on the Weser, and L4 on the Elbe. The maximum in Russia is perhaps mostly regarded as the equivalent of the German Saale glaciation (see p. 955).

An easterly migration has been discovered in the Permo-Carboniferous glaciation of South Africa.[664]

Causes of migration. Migrating ice-centres have been variously explained; shifting poles,[665] combined with continental displacement[666] or due to a clockwise movement of the Sial (see p. 1538); differential earth-movements,[667] e.g. in Canada, the Alps and north-west Europe; "sympathetic glaciation" (see below); changes in the paths of cyclones; marginal precipitation on the ice-sheets[668] and their tendency to starve in the lee[669] (the Novaya Zemlya glaciation has for this reason been linked with the last glaciation[670])—all have been invoked. A steady concentric expansion of an ice-sheet is seemingly glaciologically inconceivable.[671]

The North American ice-sheets grew eastwards from the Cordillera[672] with westerly winds, possibly by a progressive Cordilleran uplift across these winds[673]—the Ice Age, it has been said, is not yet at its climax in Greenland[674]—though it is much more likely that the rain shadow to the east of the Cordillera arrested its growth, just as farther south it carried the ice-front only to the international boundary[675] and in lateglacial time caused the Laurentide ice to disappear from west to east.[676] The ice developed westwards from Greenland[677] or much more probably from the Labrador uplands[678] by easterly winds,[679] which caused the southern limit of the ice-sheet to be more southerly than in Europe (see p. 641), or to windward by westerly winds,[680] aided by precipitation from the Gulf of Mexico and the Atlantic. Enquist,[681] in a version which was later modified by E. Antevs,[682] reconstructed three stages in the growth of this ice-sheet; a first, when westerly winds built up the Keewatin ice eccentrically with respect to the Cordillera following an initial glaciation in the western mountains; a third, when through the displacement of the Icelandic Low (because the Icelandic Ridge rose and excluded the warm waters from the Arctic Ocean), moist north-east winds replaced the present north-west land wind and the ice was eccentric to the mountains of Labrador—this postulates high pressure over the northernmost Atlantic and, apparently, pre-existing ice-sheets in northern Europe and Greenland[683]; and a second or intermediate stage of indefinite winds when the Keewatin ice was independent of the western mountains and thinned and contracted.

While the ice-sheets of Greenland and Antarctica probably grew from a coalescing of valley and plateau glaciers on highlands,[684] the problem of how the ice-sheets, e.g. the Keewatin ice, grew on low plains under conditions which are difficult to harmonise with the relief awaits a satisfactory explanation. The effective precipitation barrier of the Rocky Mountains may have been sufficiently depressed by the weight of the Cordilleran ice or by other causes to permit the winds to carry across considerable precipitation to the

east side.[685] The statement[686] that ice-sheets must have had low and not mountainous centres is unconvincing though Scandinavia, had it been as low as the Laurentian region, might, it is said, have had an ice-sheet.[687] Equally unconvincing is the suggestion that ice-sheets grew by a general continental uplift (see p. 123)—connected possibly with a shifting of the pole and of the ellipsoidal form[688]—or by successive additions of river-ice along valleys, as was postulated by Rink[689] for ice-sheets generally and by E. v. Drygaski[690] for the Keewatin and Siberian ice in particular—these may, however, have been incorporated in the advancing ice-sheet and have helped to accelerate its advance.[691] Scheuchzer[692] imagined that the Alpine glaciers grew from below by a freezing of springs. More probably, such ice-sheets grew eccentrically by strong condensation from marginal regions towards the interior[693] or from an elevated land, as imagined above. Yet the 1200 km which

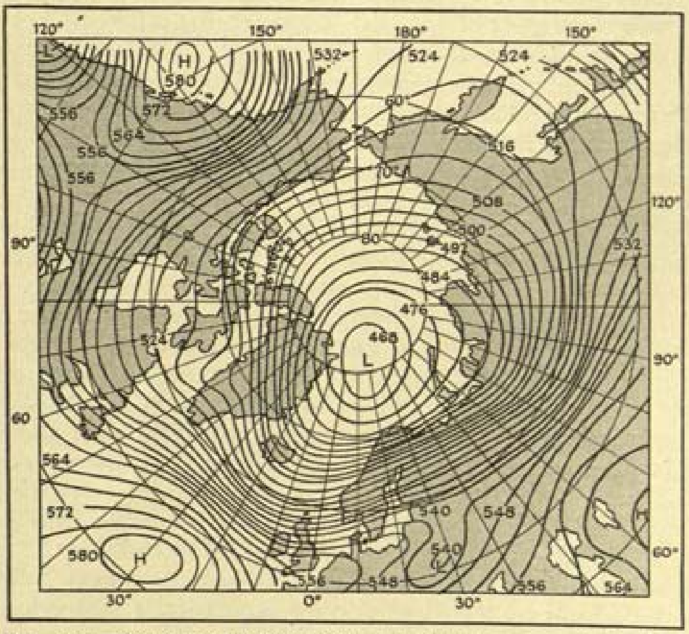

FIG. 119.—Example of a high-index or circumpolar zonal circulation. Contours of the 500-mb surface (in tens of dynamic metres) for 11 January, 1949 at 0200 G.M.T. F. Baur, *1903*, p. 823, fig. 5.

separates the Keewatin centre from the western mountains makes such a causal connexion unlikely in this case.[694]

The eccentric position of the Pleistocene ice-sheets with regard to the North Pole—they extended into lower latitudes on either side of the North Atlantic Ocean—has been ascribed to a shifting of the poles (see p. 1538) or to the great quantities of drift-ice over the North Atlantic[695] which, in contrast with the North Pacific, received ice draining from the whole of the Arctic Ocean.[696] The Pacific's open character doubtless explains the small size of the Cordilleran glaciation of North America compared with that of Scandinavia and the minor glaciation of north-east Asia compared with the glaciation of north-east America.[697]

Recent methods in North America of long-range weather analysis and fore-

casting from studies of the zonal circulation[698] are based upon the "zonal index" of the general atmospheric circulation in the northern hemisphere, including the velocity of the westerly winds in the belt between 35° and 55° N. Lat. A high-index and a low-index pattern are distinguished: no dynamically stable intermediate stage exists. In a typical high-index pattern (fig. 119), the subtropical "highs" and the subpolar lows over the oceans are well developed and extend eastwards over the continents, thereby giving rise to a "zonal" arrangement of the pressure and wind patterns, and the polar highs which send cold polar air southwards over these parts of the continents. Low-index conditions (fig. 120) are characterised by a "cellular"

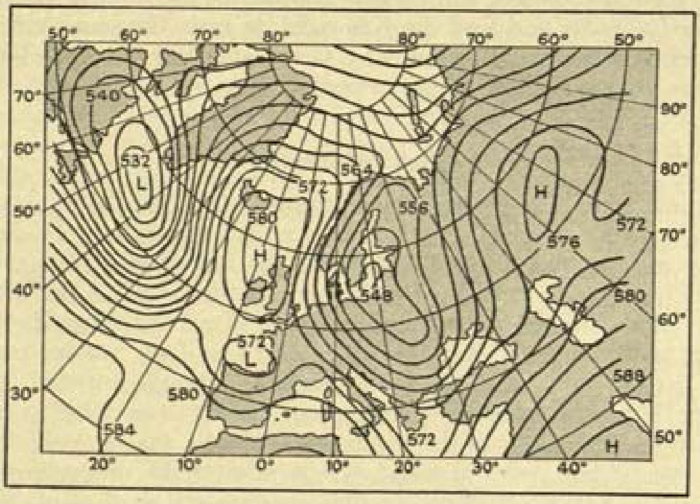

FIG. 120.—Example of a low-index or meridional circulation. Contours of the 500-mb surface (in tens of dynamic metres) for 23 June, 1949, at 0200 G.M.T. F. Baur, *1903*, p. 823, fig. 6.

disposition of the lows and highs, with a north-south rather than an east-west orientation of the major axes and meridional movements and of heat energy. In the southern hemisphere the zonal wind system at sea-level is stronger, is situated farther equatorwards and varies less with the seasons, and the cellular pattern is less pronounced. The double sunspot cycle shows contrasting high- and low-index patterns in pressure, temperature and precipitation in the higher latitudes of the northern hemisphere.[699] Subtropical highs and subpolar lows are split up and displaced southwards; and polar highs extend over western as well as eastern parts of the lands.

R. F. Flint,[700] arguing deductively from these premises, reconstructed the Pleistocene meteorology of North America in the following way. The cooling at the beginning of the Wisconsin (among other) glacial age set up a high-index pattern. The accompanying cyclonic storms increased the snowfall in western Canada and Alaska and the highlands of Quebec and, less importantly, of Labrador or those of the Alberta Low type and, moving eastwards north of the Great Lakes, brought heavy snow to eastern Canada and Labrador and ultimately an ice-sheet. With the growth of these ice-masses in east and west, a low-index pattern developed and the eastern ice expanded westwards.

A rise of temperature induced once more a high-index circulation. This

resulted in a melting back of the ice in western America but, with the inbreaks of cold air from the ice-sheet in the rear of the Alberta Low type, the Tazewell ice expanded to its maximum while the Iowan ice was shrinking. Similar fluctuations in index values explain the growth of the Mankato ice west of the Mississippi River and the more rapid shrinkage of the Mankato ice between Hudson Bay and the Rocky Mountains. H. C. Willett[701] has emphasised the importance of tropical maritime moisture penetrating the interior of the continent in winter, and H. Flohn[702] has reconciled with a meridional type of circulation such features as the glaciation of China, the Keewatin ice-sheet—the cold pole over the Canadian Arctic archipelago was strengthened and displaced southwards and caused cyclones to travel northwards over Labrador and feed the Keewatin ice from the south-east and the polar anticyclone (which explains why Greenland and the Canadian archipelago were not much greater glacierised).

5. *Effects of Ice-sheets*

Minimum area of glacial anticyclone. The minimum ice-cap required to develop a glacial anticyclone is by no means easy to determine. Brooks,[703] making the attempt, estimated the minimum diameter at 700–1000 miles (*c.* 1100–1600 km). Present-day ice throws a little light upon the problem. Both Ellesmere Land and the north island of Novaya Zemlya have permanent anticyclones[704] and Grinnell Land may have one for part of the year.[705] North-East Land, on the other hand, though reputed to have a permanent[706] or intermittent[707] anticyclone, seems to be without one[708] to judge from the behaviour of the winds and synoptic analyses; the local geostrophic winds are only gradient winds reinforced orographically and mechanically. Vatnajökull is too small to exercise any permanent effect upon the air circulation.[709]

Pleistocene evidence is not very illuminating though the Alps may have had a weak and capricious anticyclone[710]—lateglacially, when the temperature lowering may have been 7–9°C, the Azores anticyclone may have extended as a wedge into central Europe over the Alps[711] though, with the shift of the Azores anticyclone to the south, this seems unlikely.[712] The fact that, while the glacial sands in the periglacial area of the Scandinavian ice-sheet show evidence of extensive wind-action which diminishes southwards, those about the British and Alpine glaciations do not show this action[713] suggests that these smaller ice-caps lacked a glacial anticyclone.

The ice-sheets in their early stages were fed by moist winds from the outside but later developed the characteristic autocirculation. This was at first feeble and spasmodic[714] and there is virtually no evidence of when it began. Harmer's suggestion[715] that the upper Pliocene (Red Crag and Walton Crag) shell-banks of East Anglia implied an east wind from an anticyclone over a Scandinavian *mer-de-glace*, since west winds throw up such shells on the Dutch coast to-day, is doubtful; for such winds might blow on the solar-cyclonic hypothesis (see p. 1549) before the ice-sheets developed,[716] and a Scandinavian ice-sheet at this very early date seems unlikely. The absence of loess from the early glaciations (see p. 1027) may point to a lack of contemporary anticyclones.

The date of the anticyclone's disappearance is also somewhat undecided though without doubt its early shrinkage caused the distant effects to dis-

appear and the pluvial climate of the Mediterranean, for example, to deteriorate very rapidly. A high pressure system covered the Scandinavian ice when this commenced to fall back from the limit of the last glaciation[717] and probably lasted until the ice receded from the Baltic[718] (the westerly drift of erratics in the lateglacial sea of Västmanland may have been due to bergs[719] or sea-currents[720]), i.e. to the Ra moraines[721] or the time of the Yoldia Sea,[722] of the ousting of *Dryas* flora by temperate plants,[723] of the periglacial dunes of Carelia outside the Salpausselkäs,[724] or of the Ancylus dunes of the Oder mouth.[725] Northerly winds deposited loess-like deposits in Mark Brandenburg after the ice had retreated considerably from the limit of the last glaciation[726]—they were in existence during the Pomeranian stage[727]—and Scania in general, like Latvia, Estonia and Jaeren, had numerous aeolian pebbles.[728]

The Salpausselkä readvance (see p. 1172), of 12,000 years ago, has been linked with a temporary increase of snowfall brought about, not by a fall of temperature, but by the disappearance of the anticyclone and the entry of cyclones into the Baltic region.[729] At that time, the diameter of the Scandinavian ice-sheet had contracted to almost 1000 km, a figure which agrees very closely with the minimum size deduced by Brooks[730] (see above). The transatlantic correlation provided by radiocarbon dates (see p. 1526) argues against this explanation, for the readvance since the Laurentide ice-sheet was then much larger.[731]

The anticyclone had vanished when warm and moist south-west winds blew over the Littorina Sea[732] and a forest flora, previously thrust far from the ice, lived near the ice-edge in south Sweden[733] (see p. 1411): north of Scania and of Jaeren cryoturbation and continental wind-action were virtually absent.[734] In the Fens of England, the forest trees, with crowns shaped by the prevalent south-west winds, all fell to the north-east.[735] The anticyclone was most probably absent during the preceding Boreal period, to judge from the orientation of the tree trunks in the submerged forests of Lancashire and north and south Wales,[736] and during the whole of postglacial time farther south as the direction of the filling up (*Verlandung*) of the Federsee, Upper Swabia, and of the lakes in the Baltic region bears witness.[737] The storm or gale-terraces, found on the west sides of osar, and the orientation of the local glaciers and the direction of the drainage channels in middle Sweden, are also suggestive.[738]

The anticyclone fluctuated seasonally in later time; its influence was not fully felt while the Swedish inland-dunes were forming[739] and was insignificant when those of Brattforsheden in Sweden were accumulating.[740] Yet it is doubtful whether, as suggested, it persisted into Finiglacial or Ancylus time[741] or the time of the dunes of north Sweden[742] or whether the absence of a steppe period from south Sweden is attributable to its persistence.[743]

American evidence is both meagre and contradictory. The distribution of the drifts about the ice-lobes in Ohio,[744] the strength of the beaches even at the stage of Lake Maumee[745] (see p. 473), and the dissolution of the ice by evaporation on the Canadian plains[746] indicate west winds as now, as do the shells and trees, suggestive of a climate no colder than the present,[747] found in other lateglacial lakes. Nevertheless, the prevailing southerly pointing hooks in glacial Lake Champlain have been related to a glacial anticyclone[748] and the sand dunes of Quebec to easterly winds even much later.[749]

Secondary effects of ice-sheets. Weather changes are to-day most intense in winter because the contrasts in temperature between the equator and the poles, between ocean and continent, and between land and adjacent bodies of water are then most marked. In like manner, the Pleistocene ice-sheets had manifold and far-reaching effects. They heightened the temperature and pressure contrasts in the various latitudes, in particular between the Fennoscandian ice and the ice-free lands of central Europe and Asia in summer[750] (producing violent storms along the margin of the ice-sheet[751]), between the North American ice-sheet and the Gulf of Mexico, and between polar and equatorial regions generally. Contrary to Penck's view,[752] which argued, for example, that since the snowline in Germany actually rose towards the ice the latter must have exerted a very small influence, and that of others[753] including A. Wagner, according to whom periods of ice-advance coincided with periods of weaker circulation (so that in Europe the edge of the anticyclone lay in winter in north Germany, in summer south of the Alps[754]), the ice-sheets strengthened the air-circulation of the globe.[755] They pushed the polar front equatorwards, narrowed the tropical belts with their dry and hot conditions (see p. 1137), shifted and quickened the sea-currents (see p. 1093), increased the precipitation in the lee of the oceans,[756] and probably depressed the tropopause by 1 km.[757] There was a marked increase of storminess in middle latitudes and of the effective operation of the evaporation-precipitation cycle.[758] The North-east Trades were more vigorous and were nearly as strong, if not stronger than the South-east Trades, with important consequences upon the ocean currents[759] (see p. 1093).

These secondary effects were enhanced by the anticyclones which existed over the North Pacific Ocean (doubtfully), over the Arctic Ocean,[760] and notably over the North Atlantic, either permanently[761] or during the winter seasons only,[762] because the northern seas froze over and more abundant drift-ice chilled the adjacent lands, as is shown for modern Iceland.[763] The anticyclones extended the continental climate, cooled the middle latitudes, and thrust the ocean currents southwards. The summer isotherm of 40°F (4·4°C) lay over the North Atlantic, except in the north-east, its position coinciding roughly with the present winter isotherm of the same temperature.[764]

The ice-sheets by an autocatalytic action also intensified the conditions which originated them; they imposed a cooling upon the primary fall which had influenced the whole earth and initiated glaciation (see p. 644). This sequential lowering, which Pilgrim[765] mathematically examined and named the *Inlandeiswirkung* (some glacialists[766] erroneously induce the glacial cold in this way and not by general forces), is seen in a minor form to-day in the effect of the arctic ice on the weather of north Russia and Siberia,[767] and of a frozen Hudson Bay and Sea of Okhotsk on the adjacent land. The ice refrigerated the air above it by increasing its reflecting power[768] (see p. 659); caused fogs and prevented the passage of the sun's rays[769]; lifted the surface into regions of cold air[770]; and gave rise to the ice-winds and cold fluvioglacial streams. It cooled the contiguous seas by invading them, as around the British Isles, by freezing them, as in higher latitudes,[771] and by its melt-waters, e.g. those which discharged into Delaware and Chesapeake bays and with the icebergs probably produced a fog belt along the coast. It also augmented the cold by increasing the amount of drift-ice; for shelf-ice and sea-ice exert a continental influence, though this is milder than the land climate, heat being conducted through the ice from below, just as frozen Lake

Baikal mollifies the winters of its shores.[772] The secondary effects changed a locally restricted phenomenon into one of continental dimensions.[773]

Sympathetic glaciations. Thus ice-sheets, both directly and indirectly, had a formidable power of depressing the snowline[774] and intensifying and spreading the glacial cold. Many writers, indeed, regard the ice in the peripheral zone as a "sympathetic glaciation", induced by the southerly displacement of the belt of storms,[775] as in the case of Ireland, Wales and north Ural Mountains, or by the cold of the major ice-masses.[776] For example, the Scandinavian ice produced the sympathetic glaciations of the Alps,[777] Vosges and minor centres of the German Mittelgebirge,[778] Pyrenees,[779] Caucasus[780] and Scotland,[781] its oscillations being faithfully mirrored in the Alps, Pyrenees and Mittelgebirge.[782] The Scottish glaciation was in turn responsible for the sympathetic glaciation of Ireland.[783]

The easterly migration of the Scandinavian iceshed and its attendant anticyclone was reflected in the lessened Alpine glaciation during Günz-Mindel times[784] and the Mittelgebirge glaciers grew when the Scandinavian anticyclone withdrew and moist west winds replaced the dry east winds.[785]

The feeble and short-lived glaciation of the Catskill Mountains in North America has been associated with snows drifted out from the ice on the north[786]—the finest cirques face south. The glaciations of Tasmania and New South Wales[787] and of New Zealand[788] have in like manner been linked sympathetically with the vaster Pleistocene Antarctic refrigerator. It has even been held that the polar glaciations alone were primary and occasioned the cold of the rest of the globe,[789] including the tropics, or that the glaciation of the northern hemisphere created that of the southern hemisphere[790] and imposed its rhythm of glacial and interglacial periods upon this hemisphere.[791]

While the extensive development of ice in the northern hemisphere may have caused this hemisphere to influence the southern hemisphere and not vice versa as now,[792] and while it would be idle to deny that vast ice-sheets modify profoundly their peripheral zones, it would be foolish to extend this influence in the ways just mentioned or beyond a limited distance: their dry foehn winds may even raise the snowline about them.[793] The glaciers on the highlands and the terrain outside the ice-sheets owed their existence mainly to the world-wide cooling. The deep depression of the Pleistocene snowline in the moist tropics cannot be regarded as a sympathetic result.[794]

Temperatures along ice-borders. The actual temperatures in the peripheral regions of the Pleistocene ice are difficult to determine since an appeal to modern representatives in Greenland and the Antarctic is apt to mislead. These vary considerably in the mutual relation of temperature, precipitation and ablation[795]—they differ in their latitude and in their relationship to the westerly winds. They also may not be taken as norms (see p. 1061) since the Pleistocene ice-sheets protruded into warmer seas and into much lower latitudes (unless the poles or continents have moved). Nevertheless, the temperatures can be estimated from the fall of the snowline, from solifluxion phenomena and from palynology (cf. p. 1072).

The climate of Greenland has been described by H. Petersen[796] and that of ice-margins generally by O. Nordenskiöld[797] who distinguished three quite different types of glacial climate; a maritime type, e.g. in South Georgia, South Orkneys, Spitsbergen and Iceland, with small oscillations of temperature

and cool summers; a continental type, as in North America and west Greenland, with dry, warm summers (10–15°C), cold winters (−15° to −20°C), wide temperature oscillations, high evaporation, small precipitation, lakes without outlet, saline efflorescence, and wind action and rock-weathering similar to that of arid regions[798]—the "steppe" in West Greenland is really an arid or salt tundra; and a widely distributed glacial type, e.g. in north Greenland, Antarctica and possibly Franz Josef Land, having summers below 0°C and winter temperatures of −20° to −40°C.

It is difficult, as just observed, to refer the Pleistocene ice-margins to these types because they differed markedly in latitude from their modern successors and ended in continental regions. Moreover, there is every reason to assume that the climate varied greatly along the ice-fronts, e.g. in Europe (see p. 1079), and during the several phases of glaciation. Thus in west Europe the oceanic climate of the earlier stages gave place to more continental conditions later. We may believe that much of Europe, including Germany and especially the east, belonged to the strictly continental type[799] and that the maritime type in the northern hemisphere played little part except in western Europe and western North America.

Nevertheless, the evidence, though meagre, agrees in suggesting low temperatures. Thus the treeline, as in Europe (see p. 1071), was greatly depressed; solifluxion features (see p. 1075) and the *Dryas* flora (see p. 1066) were widespread and give north Germany, for example, a July temperature not exceeding 10 °C[800] and an annual temperature of under 0°C.[801] The depth of the ice-wedges which shallowed away from the ice-edge in central Germany suggest a mean summer temperature in Thuringia of 3°C and a depression of *c.* 11 °C.[802] Other calculations give the ice-corridor in north Germany where it was narrowest a mean January temperature of at least 10°C and a July temperature of 18°C[803] (cf. p. 1073). The lowering of the mean annual temperature may have been 13·4°C, of the summer 9·3–11·0°C, and of the winter 18°C.[804]

Foehn winds, varying in strength, duration and range as in modern Greenland[805] (they are rare or wanting in the north), probably blew throughout the year, especially in spring,[806] but were generally of the nature of ice-winds that kept the air at or below 0°C.[807] Temperatures and winds probably varied according to the season over both the ice and the extraglacial zones (see p. 534); persistent cloud probably lay above the margin of the Laurentide ice during summer.

Tendency of ice-sheets to self-perpetuation. Snow and cold tend by their presence to produce circumstances which make for their continuance and increase. Similarly, ice-sheets, by inducing special conditions, physical and meteorological, tend to perpetuate themselves. They augment the snowfall upon their surface by chilling the air and raising their level out of the zone of ablation (see p. 654); they prevent the summer heat from warming the air, since the heat is spent in melting the ice; they radiate cold winds, reflect more of the sun's radiation and lessen its absorption; and, by lowering sea-level by abstraction, in effect lower the snowline. Agassiz[808] therefore suggested that the present glacierisations, speaking broadly, were not a product of the present climate. Later writers, accepting the dictum, have regarded those of Iceland[809] (where the ground under the plateau glaciers is below the existing snowline), Alaska,[810] Spitsbergen[811] and above all Greenland[812] as relics of the Ice Age which, if once removed, would not return on their present

scale. The "Baffin type" of highland ice of Baffin, Bylot, Devon and southern Ellesmere islands is also a relic[813]: it does not reach the snowline and has light precipitation, short cool summers and long cold winters and great residual cold. In all cases, while the form persists, the substance has changed—calculations suggest that the Greenland ice-sheet has been at least twice renewed since glacial times.[814]

This disharmony does not hold for the glaciers of the world, as J. Payer[815] believed, and is highly improbable for the thin Icelandic glaciers[816] (except possibly Vatnajökull[817]), or for those of Scandinavia and Spitsbergen or of the Alps and other high ranges of middle or tropical altitudes, which are probably in rough equilibrium with the present climate—they respond almost immediately to current weather and lost most or all of their ice during the postglacial warm period (see p. 1494). The Glacial period, however, may have thrown its icy shadow forward in Greenland, whose glacierisation is not fully explained by the present topography and climate (as is occasionally maintained[818])—L. R. Wager[819] placed its inception during the Miocene uplift. The Antarctic ice is no doubt responsible for its own present summer cold and violent storms.[820]

This time-lag, which was very wide in the case of the larger ice-masses, caused the ice-sheets to linger into and curtail interstadial and interglacial time,[821] especially during the shorter epochs and in the central areas where the ice might linger from one glaciation to another[822] and even to glacierise both hemispheres simultaneously.[823] Thus some assume for this reason that the Alpine ice in places lasted through the Riss-Würm interglacial,[824] that the second phase of each glaciation was longer than the first because retardation gave a start to the second phase[825] and that this action caused the geochronological discrepancies between the calculated figures of Milankovitch and those arrived at geologically.[826] Thus Milankovitch (see p. 1544) believed that the nine glaciations of his curve and the marginal fringe of glaciation were reduced to four in the subcentral belts and to two only in Scandinavia and about the North American centres. The Antarctic ice may have persisted throughout the Glacial period for this reason[827] (cf. p. 918), and by influencing the eustatic fluctuations of sea-level to only a slight extent (13–17%) may explain why Pleistocene sea-levels appear to be related only to the glacial succession in the northern hemisphere[828] (cf. p. 1359). The retardation, however, may have been relatively small for the earlier phases.[829]

The tendency, by the operation of the anticyclone and the centrifugal broom, also carried the ice into the later Pleistocene stages after the conditions favouring its production had passed away. The retardation varied locally and was greater, for example, in North America than in north-west Europe[830] and in the latter than about the Alps.[831] The difference of 4000 years between the date of 18,000 years ago calculated by De Geer for the Pomeranian phase and the figure of 22,100 years assigned to this phase by Milankovitch's calculations has been referred to this tendency.[832] The relatively warm climate of Yoldia time may also be connected with this action.[833] Wegener,[834] basing himself upon present Greenland, argued that the ice survived until the temperature was at least 7°C higher than when it was formed—it is estimated that the Greenland ice-sheet and the ice in the Arctic Ocean lower the temperature north of 40° N. Lat. by about 5·6°C.[835] The final dissolution of such thinning ice-sheets, with more or less stable ice-edges but rapidly rising snowline, was manifestly rapid[836] (see p. 1158).

The effects of these and other changes in lower latitudes will be discussed in a later chapter (see ch. XL).

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T. R. S. Can. 3, 25, 1931, 40. **747** *298*, 32, 34. **748** D. H. Chapman, *A. J. S.* 234, 1938, 90. **749** H. C. Cooke *et al.*, *Can. Mem.* 166, 1931, 157. **750** *1106*, 179. **751** *1570*, 439. **752** *621*, 88; *1294*, 349. **753** *1756*, 74, 94; J. Büdel, *Nw.* 37, 1950, 440. **754** J. Keindl, *M. Gg. G. Wien*, 83, 1940, 259. **755** *204*, 107; *917*, 85; *1105*, 157; H. N. Dickson, *G. J.* 18, 1901, 516; cf. A. Penck, *G. Z.* 38, 1932, 479; W. Meinardus, *Frankf. Gg. H.* 11, 1937, 95. **756** *1106*. **757** *Ibid.*; J. Keindl, *op. cit.* **758** *1903*, 381. **759** *215*, 247. **760** *1720*, 737. **761** *465*. **762** *1106*, 175. **763** C. E. P. Brooks & W. A. Quennell, *Met. Off. Gphys. Mem.* 41, 1928; T. Thoroddssen, *Y.* 4, 1884, 145. **764** *215*, 250. **765** *1323*, 46, 48; *1324*, 4. **766** *597*, 1; *598*, 51; *601*, 83; *602*, 4; *963*, 194; *974*, I, 299; *1487*, II, 544; *1771*, 389; C. E. Grunsky, *P. Calif. Ac. 4*, 16, 1927; 83. **767** W. J. Wiese, *Nachr. Zent. Bur. Hydromet. USSR.* 3, 1924, 1; *J. Gphys. Met. Moscow*, 1, 1924, 78; *B. I. hydr. Russ.* 14, 1925, 52. **768** A. Defant, *Ver. D. Wiss. I. Kopenhagen*, *1*, 5, 1942; W. Wundt, *Met. Z.* 55, 1938, 81. **769** *323*, 40; S. Meunier, *G. Zbl.* 1903, 298. **770** *205*; F. Kerner, *SB. Ak. Wien*, 131, 1922, 153. **771** C. E. P. Brooks, *N.* 118, 1926, 54. **772** C. H. Pollog, *M. Gg. G. Mun.* 17, 1924, 165. **773** *1861*, 155; cf. E. J. Öpik, *Contr. Armagh Obs.* (9), 1953, 3, 26. **774** *1323*, 47. **775** *834*, 134. **776** *70*, 67; *1487*, II, 515. **777** *204*, 29; *205* (2), 65; *598*, 51; *1203*, 205; G. de Mortillet, *CR. C. Arch.* 1891, 110. **778** *529*, I, 260; W. Wolff, *Nw. Wschr.* N.F. 1, 1902, 303. **779** *798*, 215; N. O. Holst, *S. G. U.* C, 180, 1899, 126. **780** *Ibid.* **781** *1001*, 231; R. M. Deeley, *G. M.* 1916, 116; N. Ekholm, *Q. J.* 58, 1902, 39. **782** *204*, 29, 57; O. Jaekel, *Z. D. G. G.* 69, 1917, 161. **783** *204*, 58; *1001*, 231. **784** *204*, 56. **785** K. Olbricht, *Vh. GTag*, 1910, 30. **786** *1404*, 115. **787** *204*, 110. **788** W. Wolff, *Nw. Wschr.* N.F. 2, 1903, 7. **789** *1252*, 38, 53; *1487*, II, 544; *1720*, 727. **790** *330*, 444. **791** *1720*, 729. **792** G. Viete, *Tellus*, 2 1950, 107. **793** *1290*, 228. **794** *913*, 914; *919*, 56. **795** *30*, 342. **796** *1741*, 257. **797** *1198*, 509; *1200*, 10; *Ups. B.* 15, 1918, 35. **798** *772*, 224; *1200*, 14; W. H. Hobbs, *G. S. A. B.* 41,1930, 89. **799** *120*, 137; *917*, 70; *1290*, 222; *1291*, 5; A. Blytt, *Bot. Jb.* 1893, BBl, 41, 27; A. M. Hansen, *Vid. Selsk. Skr.* 1929 (5), 203; cf. H. Poser, *Nw.* 34, 1947, 17; E. Reichel, *Z. Gl.* 22, 1935, 73; W. Wundt, *ibid.* 46; W. Soergel, *JB. M. Oberrh. G. V.* 31, 1942, 59. **800** C. Gagel, *Z. D. G. G.* 75, 1923, 25; E. Werth, *Ber. D. bot. G.* 43, 1925, 391. **801** P. Range, *Z. D. G. G.* 75, 1923, 36. **802** W. Soergel, *ibid.* 88, 1936, 223. **803** *1290*, 227. **804** W. Soergel, *JB. M. Oberrh. G. V.* 31, 1942, 80. **805** *695*, 37; *770*, 68; *927*, 362; *1741*, 265; L. Koch, *Z. Gl.* 17, 1929, 232. **806** *895*, 157. **807** *Ibid.* 158. **808** *15*, 13. **809** *G. J.* 80, 1932, 460; J. Keindl, *Z. Gl.* 20, 1932, 17. **810** H. Gannett, *Nat. G. M.* 10, 1899, 507. **811** *575*, 690. **812** *65*, 17; *145*, 95; *449*, *108*; *737*, 59; *931*, 219; *1198*, 641; *1200*, 34; *1623*; *1741*, 435; L. C. W. Bonacina, *Q. J. R. M. S.* 73, 1947, 85; N. Ekholm, *op. cit.* 38; A. G. Nathorst, *Ö. Vet. Ak. F.* 1891, 197; C. Rabot, *CR. A. Av. Fr.* 1890, (1), 42. **813** P. D. Baird, *J. Gl.* 2, 1952, 2. **814** *755*, 116. **815** *M. Gg. G. Wien*, 12, 1869, 432; *P. M.* 1871, 125. **816** *847*, 55; G. Manley, *Q. J. R. M. S.* 73, 1947, 91. **817** L. Hawkes, *ibid.* 73, 1947, 89. **818** *748*, 108; *974*, I, 314. **819** *G. M.* 1933, 145. **820** *429*, 688. **821** *323*, 125; P. Beck, *M. nw. G. Thun.* 4, 1939, 67; T. F. Jamieson, *G. M.* 1906, 534. **822** *1323*, 49, 57. **823** *119*, 335; *125*, 169; *1323*, 60; W. Wundt, *Z. Gl.* 22, 1935, 52. **824** *125*, 167. **825** *636*. **826** *931*; *1121*, 172; W. Wundt, *op. cit.* **827** *Ibid.*; F. E. Zeuner, *Ann. Mag.* *11*, 1, 1938, 394. **828** *Ibid.* 395. **829** *1861*, 168. **830** F. E. Zeuner, *op. cit.* 391. **831** *230*, 109; J. Büdel, *Nw.* 37, 1950, 448. **832** *1860*, 56. **833** H. W:son Åhlmann, *G. F. F.* 64, 1942, 93; A. Cailleux, *S. G. Fr. Mém.* n.s. 21, 1942. **834** *1777*, 105. **835** *205* (2), 218. **836** *1323*, 47; *1840*, 468.

Chapter XXXII

WORLD GLACIATION

1. General

Oncoming. The Pleistocene glaciation, equal in severity to any in geological history[1] (see fig. 121), was not ushered in suddenly as earlier believed[2] or occasionally stated in recent years.[3] It marked the climax of a gradual and prolonged climatic worsening and a sharpening of the climatic zones. From their position during the Eocene,[4] the isotherms wandered equatorwards,[5] in both the northern and southern hemispheres; the temperature in central Europe fell 14–15°C and the winter isotherm of 0°C moved southwards in conformity. In eastern Asia, an essentially homogeneous forest shifted from an average position of 55° N. Lat. in the Eocene to 32° N. Lat. in the Pliocene.

In the lower Tertiary,[6] the climate of the whole earth was warmer and more uniform, and the latitude of the boundary of the warm zone was on an

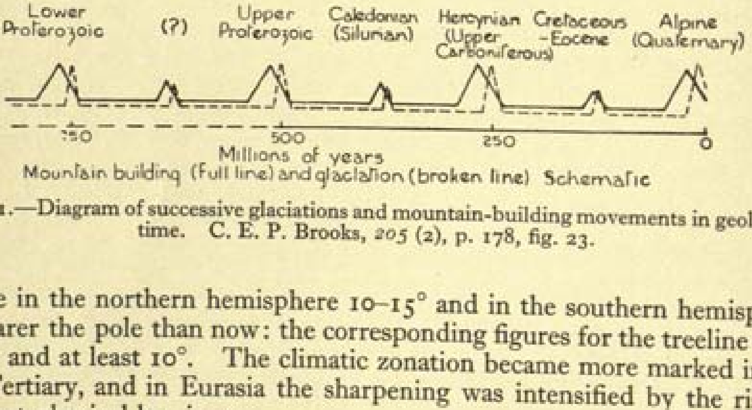


FIG. 121.—Diagram of successive glaciations and mountain-building movements in geological time. C. E. P. Brooks, *205* (2), p. 178, fig. 23.

average in the northern hemisphere 10–15° and in the southern hemisphere 10° nearer the pole than now: the corresponding figures for the treeline were 20–30° and at least 10°. The climatic zonation became more marked in the later Tertiary, and in Eurasia the sharpening was intensified by the rise of east-west physical barriers.

The flora, branches of a common circumpolar, Arcto-Tertiary flora, probably largely derived from an Arcto-Cretaceous flora, migrated southwards in the northern hemisphere.[7] The Eocene had a preponderating Indo-Malayan flora mixed with plants related to present North American-East Asian types, and with palms and tropical plants and fruits, as in the London Clay[8]; subtropical fig trees grew in the Hampshire Basin during a later stage (Bournemouth Beds). Soils, landscapes and the fauna, which included alligators, crocodiles, Nautilus and the larger Volutes, now confined to tropical seas, are at one in finding that the climate was tropical or subtropical. Britain's mean annual temperature during the Eocene may have been about 21°C.[9]

In Germany,[10] the Eocene flora included Araucaria, Sequoia and Sabal and resembled that in southern Asia and South Africa, while *Gingko, Sequoia,*

Sabal, Phoenix, Chamaerops, Magnolia, Robinia, Olea, Nerium and *Taxodium distichum* grew during the Oligocene. The Carpathians had similar tropical or subtropical floras of Tertiary age.[11]

F. Unger[12] and O. Heer[13] unveiled the gradual change in Switzerland from tropical to warm temperate climate. The extremely rich flora of Oeningen in the neighbourhood of Boden See, with its 475 species of plants and the associated insects (922 species), shows that the Miocene climate, though colder than previously, was yet distinctly warm, like that of Madeira or south Sicily to-day—the winters were milder. South France and the central massif showed a like deterioration.[14] The Tertiary cooling in East Prussia is revealed in the ousting of the tropical Oligocene (amber) flora, with its bamboos and palms and deciduous and needle trees, by the subtropical (cinnamon and palms) and temperate flora of the Miocene,[15] and in northern Bohemia by the progressive reduction in the forests.[16] Frost marked the leaves of *Fagus attenuata* in the Miocene of Lausitz[17] (glacial deposits of this age have been reported from Iceland, Italy and the Cevennes[18]) and of Pliocene plants near Frankfurt-am-Main,[19] though the climate was generally mild and moist[20] (see below). During the Miocene, when the annual temperature of Spitsbergen was 11°C and of Disco Bay 13°C, the whole flora of western Europe was of the Chinese-American type, palms, cinnamon, campfer trees and evergreens grew in central Europe, and the Pyrenees were still climatically similar to present Morocco[21]; the isotherms lay 12° farther north and the wind systems were correspondingly shifted. The Miocene mammalia of Europe included apes, bears, civets, mastodonts, rhinoceroses, tapirs, antelopes, muntjacs and chevrotains now restricted to the tropics of Asia and Africa.

During the Pliocene, the palms were driven southwards through 10° of latitude[22] and the present flora, with pine, fir, spruce and larch, became established in central Europe.[23] Tapir, mastodont, antelope, giraffe and anthropoid apes vanished from the continent. Monkeys, which ranged as far north as Eppelsheim near Darmstadt during the Miocene,[24] became more restricted in the lower Pliocene. Pliocene *Macacus*,[25] a monkey of Asian type, occurred in Grays Thurrock and the Cromer Forest Bed (*M. pliocenicus*), Tiglian (see p. 1043), north Italy (*M. florentinus* and *M. ausonius*), south France (*M. tolosanus*), Württemberg (*M. suevicus*), Sardinia (*M.* sp.), Hungary (*M.* sp. aff. *inuus ecaudatus*) and Rumania (*M. florentinus*) and still survives in Europe on the rock of Gibraltar (*M. inuus*)—it may be a later introduction from Africa. As late as the lower Pliocene, the climate remained warm and humid as chemical weathering in Scandinavia and central Europe and the brown coals suggest.

The Chinese and North American (Engler's Arcto-Tertiary) element in the European flora (which had a close affinity to the mountain flora of western China and had evolved in either the Himalayas or the Arctic during Tertiary time[26]) had serious toll levied upon it throughout the Pliocene[27] (fig. 122). The percentage of extinct and exotic seeds which in the lower Pliocene Pont-de-Gail was 94 and in the Reuverian of Limburg 88 was reduced to 64 at Castle Eden (Co. Durham), to *c.* 40 in the Tiglian (see p. 1043), and to 5 in the Cromerian.[28] The corresponding percentages of the Chinese-North American species were 64, 54, 31, 16 and 0·74. Trees and shrubs suffered particularly severely and only the hardier species like *Quercus robur*, *Corylus avellana* and *Picea excelsa* managed to survive. The Pliocene trees, e.g. the

locust (*Robinia*), honey locust (*Gleditschia*), sumach (*Rhus*), bald cypress (*Taxodium*), tulip tree (*Liriodendron*), sweet gum (*Liquidambar*), and cotton gum (*Nyssa*), disappeared.[29] In France, only a few subtropical species, e.g. *Myrsine* and *Persea*, persisted and a striking floral change passed over the Rhône valley in the south-east.[30] Thus the North American and central European floras became markedly distinct. Plants with Malayan or Australian affinities (*Hakea*, *Tongmansia*, *Epipremnum*, and *Mimusops*) had vanished by Tiglian time[31] when the flora was closely allied to that of central Europe to-day. The Cromerian saw the European facies fully established and the disappearance of the peculiar Chinese element except for such species as still live in Europe.

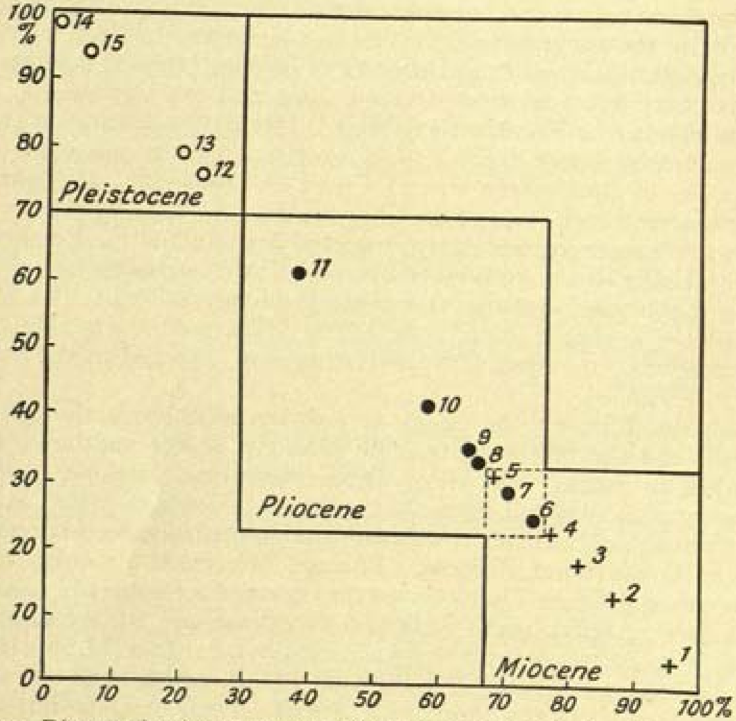


FIG. 122.—Diagram showing the decrease of exotic species (abscissa) and increase of native species of plants (ordinate) in Europe during the Miocene, Pliocene and Pleistocene. 1, Salzhausen; 2, Herzogenrath; 3, Wieliczka; 4, Niederlausitz; 5, Sośnice; 6, Pont-de-Gail; 7, Frankfurt; 8, Krościenko; 9, Reuverian; 10, Willershausen 11, Castle Eden; 12, Tegelen; 13, Schwanheim; 14, Cromer; 15, Vogelheim. W. Szafer, *B. Ac. Pol.* 72B, 1946, p. 34.

Some of the Tertiary plants survived into the first interglacial, a few into later interglacials. Thus the Reuverian contains *Pinus*, *Tsuga*, *Sciadopitys*, *Sequoia*, *Juglans*, *Carya*, *Pterocarya*, *Fagus*, *Castanea*, *Liquidambar* and *Nyssa*, the Tiglian *Tsuga*, *Juglans*, *Carya*, *Pterocarya*, *Fagus*, *Liquidambar*, *Magnolia kobus*, *Mespilus cuneata* and *Vitis vinifera*, the Cromer Forest Bed *Hypecoum procumbens*, while *Brasenia purpurea*, *Dulichium spathaceum*, *Juglans regia*, *Buxus sempervirens*, *Ficus carica*, *Cercis siliquastrum* and *Laurus canariensis* lived on into the second interglacial[32] which in Switzerland[33] contained North American and eastern Asian *Tsuga* and

relations of the North American *Pinus strobus*, the Himalayan *Pinus excelsa*, the Serbian *Picea omorica* and the Caucasian *Fagus orientalis*.

The early Pleistocene flora in the Mainz basin,[34] which resembled the North American forest flora of the New England States and contained an eastern Asiatic element and 24% of exotic species, lacked the characteristic Tertiary forms *Taxodium*, *Sequoia*, *Gingko* and *Cinnamomum*.

The progressively falling percentages of the woody plants during the Tertiary, expressed in the following figures[35] (see p. 690): Eocene (London Clay) 97, Oligocene (Bembridge) 57, Mio-Pliocene (Pont-de-Gail) 51, Reuverian 57, Tiglian 28 and Cromerian 22, was also climatic, though the contemporaneous replacement of forest by grasses and pasture may have been connected with the development of mammals.[36] This replacement was slight at first but gained speed towards the close of the Tertiary when the grazing horse took the place of the browsing horse (see p. 1410).

The Cyprids of the gastropods, which to-day are mainly tropical or subtropical, shifted their northern boundary steadily southwards during the Tertiary.[37]

The cooling in Germany is revealed in the change in the character of the soils and in the replacement of the mixed oak forest and beech by fir and pine in the browncoal of Buchenau,[38] and in the climatic distribution of the Tertiary fish in western Germany, as set out in the following table.[39]

Percentage of fish genera in the West German Tertiary

	L. Oligocene	*M. Oligocene*	*U. Oligocene*	*M. Miocene*	*U. Miocene*
Purely tropical	11·2	0·0	0·0	0·0	0·0
Tropical or subtropical . .	44·4	17·6	15·4	5·5	0·0
Tropical, subtropical or cooler .	0·0	17·6	34·6	27·6	35·7
Subtropical-temperate or cooler	22·2	47·2	42·3	55·6	50·3
Temperate cold	22·2	17·6	7·7	11·1	14·3

It is also shown in the following figures[40] which may be taken to indicate the general climatic trend in Tertiary Europe: Eocene 22°C, lower Miocene 19°C, upper Miocene 17°C and Pliocene 14–17°C. The Klärbecken flora of Frankfurt-am-Main[41] gave a temperature resembling that of Venice or the Riviera. The mean annual temperature in France was at all stages a few degrees higher[42] and in the west during the Plaisancian (lower Pliocene) was probably 5°C higher than now.[43] Winter temperatures in Dalmatia have been estimated as follows[44]: Eocene and Oligocene 9·3°C, Miocene 6·6°C, Pliocene 2·8°C, and Pleistocene −0·7°C. The insects of western Europe show a similar climatic change.[45]

Corresponding changes characterised Russia (A. N. Krasnoff), the Carpathians[46] and the Balkans,[47] where the tropical and most of the subtropical plants died out during the lower Tertiary and the Mediterranean forms withdrew in the Pliocene to the coasts. A climatic worsening is also recognisable in the upper Pliocene (Apscheron Beds) of the Caspian region (see p. 699) in which *Cyprina islandica* occurs, in the upper Cainozoic plants of north Siberia[48] and in the Tertiary life of north-east Asia[49] (see p. 1087) though, as in North America, subtropical relics survived under favourable conditions among the predominant temperate forest. North-west Africa also showed a fall of temperature in upper Pliocene time,[50] though lateritic soils in Morocco seem to indicate a warmer climate than now.[51] The formation of calcareous

crusts shifted from central Europe in upper Miocene (Sarmatian) to the northern Mediterranean lands in the lower Pliocene, the southern Mediterranean lands in upper Pliocene, north Sahara at the end of the Pliocene and to Senegal and the Sudan in the Quaternary.[52]

There was a southerly floral movement in Japan[53] and a replacement of the temperate floras in north and east Asia[54] where the whole vast territory embracing the middle zone of Siberia, north Turkestan, Manchuria, Korea, Sakhalin and north Japan was at least as late as the early Miocene under the domination of a monotonous summer-green forest flora which also characterised Greenland, Spitsbergen, Alaska and northern Canada. Warm forms still lived during Mio-Pliocene time in the north Urals and west Siberia[55]: *Abramis*, *Blicca*, *Alburnus*, *Alburnoides* and remains of other fish have been found in the Pliocene. In northern India the tropical climate of the foothills was usurped by temperate conditions[56] and there was a migrational trend across the peninsula. North China's lower and middle Pliocene fauna consisted mainly of warmth-loving types while its upper Pliocene forms reflect colder and more arid conditions.[57] A southward shifting of *Lamprotula*, a thick-shelled Unionid, followed the Miocene in the north Tsinling region.[58]

The rich coral development of the Mediterranean region in the early Tertiary—coral reefs existed as late as the Miocene in Malta and Asia Minor as well as in the Vienna Basin and the Ukraine—gave place in the upper Tertiary to spasmodic corals which in the Pleistocene were completely banished. Trout wandered into Asia Minor, the Atlas Range and Hindu Kush.[59]

North America underwent a like change.[60] Thus the climate of the Pacific coast, which as far north as the Yukon (Sequoia, Magnolia and delicate ferns), was tropical or subtropical in the Eocene, became transitional from this to warm temperate in the Oligocene, warm temperate in the Miocene, transitional from this to subboreal in the lower Pliocene, and subboreal in the upper Pliocene. The temperature fell constantly from the Eocene onwards, though as in China there was a temporary reversal of the climatic trends in the upper Miocene; plants like the present replaced the tropical and subtropical species and many animals, including apes, wandered southwards or disappeared. The subtropical members diminished and the Chinese element retired to the south-east. Temperate forms, never quite absent, now preponderated. The older Tertiary forests had in large measure disappeared from the middle latitudes before the beginning of the Miocene: the northern limits of the region of typical Eocene species shifted southwards. In Mid-Tertiary the subtropical forest of the Pacific coast migrated southwards through 1000 miles (1600 km) to south California and Mexico, and the temperate forest of Alaska, the redwood forest dominated by Sequoia (also known from north Siberia, Spitsbergen and Greenland) moved down to Oregon and middle latitudes and grasses became more widely developed. In the Pliocene, the temperate forest was further restricted, the Sequoia element and certain species being eliminated, their modern descendants surviving in Asia.

These changes are reflected in a southerly withdrawal of the widespread subtropical forest (Goschen flora); the contraction of the temperate redwood forest (Bridge Creek flora) which in the Eocene lived north of the United States boundary, e.g. in Alaska, and in the Miocene inhabited the country south of that boundary, e.g. in Washington and Oregon; the contraction and

segregation of a north Mexican element (Tehachapi flora); the origin and expansion of a continental interior prairie; and the development of the Colorado and Mohave deserts.[61]

Floral contrasts due to differences of latitude became more recognisable, probably as a result of the relatively emerged condition of the continent in later time and of the more varied topography. On both sides of the Pacific, a zoning from middle to low latitudes became marked during the Pliocene. A like change is shown by the type of vegetation from the coast inland in contrast with the wider distribution of Miocene and older Tertiary floras both in Asia and North America.[62] The marine faunas (see below) and the vertebrates (Colbert, 1953) confirm this trend; the mammalian faunas of the late-Miocene and Pliocene indicate the development of varied environments and climatic zones. Steppe animals and plain-loving horses and many kinds of deer and antelope became prominent.

Reduction in leaf size and thickened texture characterise most of the specimens from interior localities during the Tertiary in western America and in China. The disappearance of such broad-leafed deciduous genera as *Carpinus*, *Fagus*, *Gingko* and *Tilia* apparently took place in western America at the close of the Miocene with *Ulnus* lasting on into the middle Pliocene.[63]

Although Heer's[64] inaccurate floral identifications of Tertiary Greenland, Spitsbergen and Siberia, based upon leaves, led him to false conclusions in interpreting the climate of these countries,[65] it is nevertheless true that the flora of these northern lands, with their poplars, limes, elms, planes, cedars and magnolias, was quite incompatible with glaciation. Yew, pine, spruce, poplar, birch, hazel, horsetail and grass grew near Cape Murchison in Grinnell Land (72° N. Lat.) in a cool temperate climate. Greenland at the beginning of the Tertiary had at least a Mediterranean climate[66] and the polar regions were probably unglacierised before the beginning of the Pliocene[67] (cf. p. 679). The faunas of Bering Sea and the North Atlantic (Nantucket Island) were readily exchanged as the specific identity of many marine shells in the two areas bears witness[68] (see p. 1089).

The Antarctic had a similar experience[69]: it cooled during the late Tertiary by a series of great pulsations. A luxuriant Tertiary vegetation grew in the vicinity of the Antarctic Circle,[70] at the Strait of Magellan[71] (Punta-Arenas) and in Seymour Island[72] (64° S. Lat.); certain warm-water molluscs and brachiopods of Miocene Patagonia and Chile species ranged as far south as Cockburn Island just north of Graham Land.[73] The Antarcto-Tertiary flora replaced the subtropical forests in the southern continents. Warm conifers, such as *Acmopyle*, *Araucaria* and *Podocarpus*, and angiosperms, such as *Knightia*, *Laurelia* and *Nothofagus*, wandered northwards from Antarctica and the southern tip of South America where they occurred in Eocene time.[74] The Falkland Islands[75] were preglacially well wooded with South American conifers, including Araucaria—to-day these trees do not range farther south than 43–44° S. Lat.—and warm marine shells lived in Kerguelen.[76] South America during the Tertiary had a climate which worsened increasingly from south to north.[77] Patagonia's climate deteriorated during the Pliocene[78] as did that of New Zealand[79] (this is implied by land plants and marine life) and of Australia[80] where during the Miocene, as is indicated for example by the reef-forming coral *Orbicella*, the sea in Bass Strait was 10 °C warmer than at present and in the Pliocene of Queensland fossil laterites suggest a warmer climate than now.[81]

The Antarctic, like the Arctic, furnishes no evidence of glaciation before the Ice Age[82] (see p. 596). Drift-ice has, however, been postulated for certain post-Miocene conglomerates on Cockburn Island,[83] though the bryozoan and other forms suggest a climate which is incompatible with this.[84] Glaciation seems irreconcilable with a land-connexion, so often suggested,[85] between Australia and South America during Tertiary time based on many affinities in their flora and fauna (see p. 1088).

In marked contrast with these world-wide changes and the narrowing of the tropical zone, the tropical climate itself, to judge from its flora and the freshwater molluscs of the East Indies and Indo-Malayan region, remained unaltered,[86] though the forging of land-links in central America and in other critical tropical areas caused important changes in the littoral faunas of tropical seas.[87] The Acidian fauna which developed during the Tertiary also persisted in these seas.[88]

The middle Pliocene and later changes were an important factor in the break up and segregation of the major continental Tertiary floras and their evolution into modern plant communities.

Cooling of the seas. The approach of glacial conditions was also felt in the world's seas: incoming cold shells displaced warmer ones and floating ice drifted erratics.

The Tertiary precursor of the North Sea, which gradually shallowed as its marine, estuarine and freshwater succession in East Anglia reveals,[89] became progressively colder. The marine mollusca in particular, which during the Eocene were almost tropical,[90] show a slow climatic worsening during the Pliocene and lowest Pleistocene. This is brought out in the following table[91] (which deals only with forms still living):

	Total Number	*Relative Numbers*		
		Living British	*Arctic*	*Mediterranean*
Forest Bed . . .	19	100	0 (?7)	0
Weybourne Crag .	53	100	21	0
Chillesford Crag . .	90	100	10	3
Norwich Crag . .	112	100	11	9
Newer Red Crag. .	199	100	10	18
Older Red Crag . .	148	100	2	22
Coralline Crag . .	420	100	0·5 (?0)	41

The sea of the Coralline Crag at the bottom of the series was warmer than the present as *Pyrula*, *Columbella*, *Terebra*, *Cassidaria*, *Pholodomya*, *Lingula* and *Discina* prove.

In the Weybourne Crag at the top of the succession, there was no species of exclusively southern range and arctic species had increased and were individually plentiful: *Tellina baltica* appeared for the first time. The arctic character of the slightly older Norwich Crag is proved by the predominance of *Tellina calcarea*, *Astarte borealis* and *Scalaria groenlandica*, an assemblage now found north of the Arctic Circle but then established in the British Isles as far south as 52° N. Lat. The varying percentages of northern and southern

forms among the marine gastropods[92] agree with the conclusions drawn from those of the molluscs.

This ousting of a southern by a colder element may have been owing to the closing of the Straits of Dover,[93] a deepening of the North Sea,[94] or an influx of cold currents—this may have been due to the opening of some new connexion with the Arctic,[95] possibly east of Scandinavia,[96] the submergence of a land-barrier between Scotland and Scandinavia,[97] the erection of an Icelandic Bridge[98] (see p. 1235), or a widening of the rift between Europe and Greenland.[99] It may equally well be referred to the general climatic worsening[100] which chilled the sea in much lower latitudes, e.g. in the Mediterranean and California (see below), in the North Atlantic, and in the polar basin which in Pliocene time may have been frozen over as it is to-day[101] (see above). The impoverished state of many Icenian shells may (doubtfully) have been due to a freshened North Sea which resulted when the Scandinavian ice advanced and wholly or partly blocked the northern outlet of that sea.[102]

A similar cooling, prophetic of the Glacial period, is recorded in the upper Pliocene beds of Holland[103]—the climatic change from the middle Pliocene to the Amstelian corresponded to a shift of 30° of latitude[104]—and of Schleswig-Holstein[105]; by the northern species embracing *Buccinum groenlandicum* in Norway[106]; by the mixed fauna, with cold species, in the Manx drifts[107]; and by the Pliocene *Tjörnes* formation (about 700 m thick) of Iceland[108] which registers a sinking of the sea temperature from that of the Low Countries and south Norway to that of west Iceland to-day.

The tropical character of the former central Atlantic marine fauna, e.g. echinoderms, corals, molluscs and fishes, changed considerably during the later Tertiary.[109] Much of the early fauna died out, tropical forms disappeared, and northern forms took their place. In the Mediterranean tropical genera of the sea-urchins, e.g. *Clypeaster* and *Diadema*, vanished and northern forms, e.g. *Echinus*, *Strongylocentrotus* and *Sphaerechinus*, replaced them. The glacial chill penetrated this sea during the Sicilian (see p. 1090), when the Mediterranean was seemingly much colder than now, and is recorded in the appearance in the Calabrian of such cold shells[110] as *Cyprina islandica*, *Buccinum undatum* and *Panopaea norvegica* and by the arctic *Alca impennis*,[111] a flightless bird, which has been found in Gibraltar and Otranto.

The ocean along the Atlantic coast of North America was cooled.[112] In the Miocene the tropical marine fauna, e.g. East Indian types of corals, in Florida, Georgia and the adjacent states was destroyed and replaced by a colder fauna. In the Caribbean, the temperature sank from 26–27°C to 19–20°C. The Pacific coast of North America also shows a progressive cooling from Eocene onwards[113] (fig. 123). Marine forms, colder than now, lived in the uppermost Pliocene of the North Pacific,[114] as in Alaska, Japan and east Sakhalin, and drove out the warm ones of the lower Pliocene.[115] The chilling was felt as far south as California in agreement with evidence from the land plants[116]; warm-water species of the lower Pliocene gave way completely to cold-water forms, including several now found between Alaska and Puget Sound.[117] As in the Mediterranean Sicilian, to judge from the marine fauna, the temperature, even in the shallow water, was then as cold as during any part of the succeeding Pleistocene.[118] Yet in California, where a marine transgression took place at the beginning of the Quaternary and where the Timms Point fauna is glacial, the interpretation of the

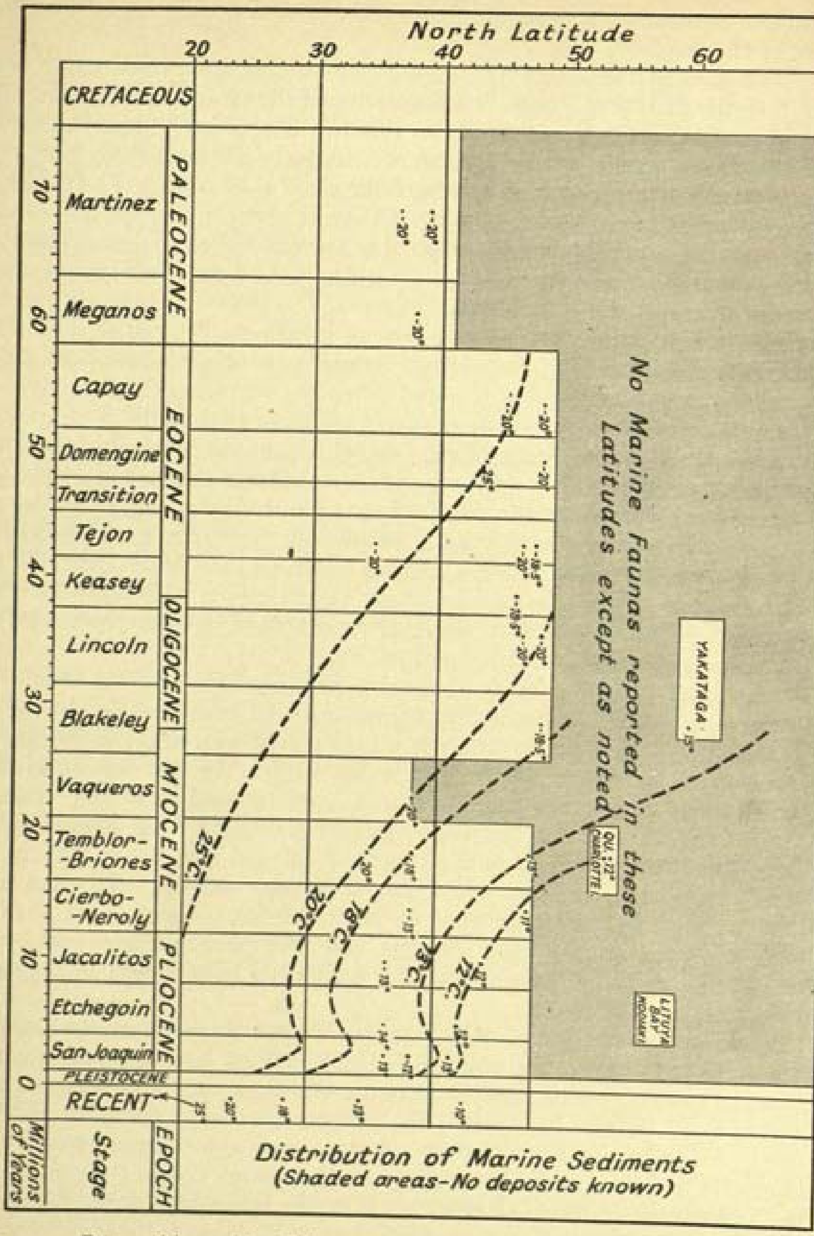


FIG. 123.—Past positions of the February marine isotherms along the Pacific coast of North America. J. W. Durham, *G. S. A. B.* 61, 1950, p. 1259.

temperature facies is difficult since there were also variations in depth and range.[119]

Other forerunners of the approaching cold are the heavily striated pebbles in the iron-stained Stone Bed beneath the Cromer Forest Bed[120] and drift erratics in stream and similar accumulations. Water-worn blocks of porphyry, up to half a ton in weight, in the Coralline Crag at Sutton, may have

been carried by floating ice[121] or by driftwood—the blocks are unglaciated and the surrounding deposits have no arctic shells.[122] Drift-ice was probably responsible for the big, unworn flints in the Red Crag[123] and its occasional boulders, up to 1 ft (*c.* 30 cm) in diameter, of porphyry, granite, basalt, vein quartz and quartzite, and for similar boulders in the Crag at Ipswich and Weybourne.[124] Erratics in the Pontian beds of south Russia[125] and occasional far-travelled pebbles in the infraglacial beach of the British Isles[126] may have had a like origin. The heavy mineral assemblage in the East Anglian Pliocene,[127] and especially in the *Leda myalis* Bed[128] (see p. 995), shows that much Scandinavian detritus was then arriving in the area.

Erratics were also rafted by ice into fluviatile accumulations, e.g. "preglacial" terraces in the Saale,[129] Tiglian beds of the lower Rhine[130] (see p. 1043), upper Pliocene at Odessa[131] and upper Tertiary[132] in Sylt, Pomerania and Brandenburg.

The upward transition in the British Pliocene from marine to fluvio-marine, littoral and fluviatile may indicate that the ice-sheets were growing and abstracting sea-water and so confirm the molluscan evidence that the Ice Age was drawing near. The fact that the present and preglacial sea-levels (strandflat, see p. 1250; infraglacial raised beach, see p. 1251) virtually coincide may signify glaciations on roughly the same scale then as now.[133]

The cooling throughout the Tertiary is now established, though it is not safe to argue without reserve from the composition of fossil faunas and floras about the climate of the past.[134] The cooling has been attributed by A. G. Nathorst, M. Neumayr and others to polar movements and to a northward continental displacement through the normal climatic belts.[135] It is in part explained by changes in the distribution of land and water[136] (involving a reduction in the supply of warm water from the south and a less efficient outlet of cold water from the arctic basin), in part by earth-movements[137] which diversified the relief and erected high mountains in so many parts of the world and in western North America also reduced the annual precipitation,[138] e.g. from *c.* 254 cm in the Eocene to 127–190 cm in the Miocene. Mountain building, by breaking up the extensive areal units, diversified the topography and climate and made the floral and faunal contrasts more marked. The draining of the Obic Sea and the widespread orogeny which narrowed and reduced the Tethys and extended the Alpine and Himalayan systems across much of Eurasia in the Old World doubtless contributed.[139] A complete explanation, however, must include those forces which caused the Glacial period and which, almost certainly, did not merely comprise geographical, oceanographical or tectonic forces (see ch. LI).

Proofs of glaciation. The nature of the proof that glaciers and ice-sheets formerly existed has been described at much length on earlier pages (see Part II). The methods have to be used with care since they are not always unambiguous; each diagnostic feature has its nonglacial imitation. Thus rounded forms resembling roches moutonnées may be preglacial[140]; terminal curvature may be made by creep[141]; striated and faceted boulders may result from mudflows or tectonic movements[142]; surface boulders may be residual from formations now destroyed[143]; and deposits resembling boulder-clay may arise in various ways.[144] Yet these features in association are conclusive proof of glaciation. Ground and marginal moraines, outwash plains, ice-eroded basins, cirques, U-valleys and fjords are other manifest signs.

The direction of flow (which, like the winds, should be designated by reference to the source[145]) is registered by folds and thrusts in the drift or underlying strata[146]; by boulder-clay inserted along bedding planes[147]; by terminal curvature, crags and tails, roches moutonnées and drumlins; by the ice-worn edges of joint cracks; by the distribution of local and foreign erratics and heavy minerals (see p. 378); by the orientation of the big boulders in the drifts (see p. 377) or on the surface,[148] or of boulders pressed into fissures in the country rock[149]; by splinters from the ends of overridden tree trunks[150]; by the fabric and size distribution in the till[151]; and by stream shadows in the lee of subglacial "nunataks" as described from north Germany.[152] Striae, most impressively universal on hills and in dales (those recorded, though almost numberless, are, like extracted fossils, but an infinitesimal fraction of those that exist or have existed), are especially valuable in giving the lines of flow or *glacivals*.[153] If indecisive, use may be made of nail-head and forking striae, crescentic gouges and associated features (which dip downstream[154]), crags and tails on rock-surfaces, plucking phenomena on grains, etc., and the bevelled lee edges of cracks or cavities. Yet even striae are strictly only locally significant[155] and if few must be employed with caution: alone, they leave the direction of flow over north Germany quite uncertain.[156] Their spotty distribution, well shown on the Glacial map of North America,[157] results from the debris content of the ice, lithology, concealment beneath drift, postglacial erosion, and variable observation and mapping. Where more obvious signs are lacking, the direction may be obtained from till fabrics.

Early stages. Decipherable history virtually begins at the time when the ice had attained its outermost limit. The protoglacial or early stages ("advancing hemicycle"[158]) are either unknown or only imperfectly discernible. Their record was obliterated by later glaciations or, if preserved, is difficult of access or interpretation and probably destined to remain obscure. In its absence, danger lurks in interpreting the advance by the final retreat and in imagining the one as the reverse of the other. This was probably not so.[159] The ice and its attendant anticyclone which made it possible for the amelioration to be well advanced before there was any marked effect[160] (see p. 679) had no counterpart in the early stages; a small adverse climatic change may initiate glaciation but a much larger change is required to dissipate an extensive mass of ice. Moreover, the configuration of the central mountains, abounding in cirques and other features inherited from the Glacial period itself, was more propitious for developing glaciers at the end than at the beginning of the period (see p. 652). The glacially created forms predestined the succeeding glaciations to develop in a similar way to that which created them.[161]

The oscillating margin of the advancing ice was during the temporary, negative phases probably unaccompanied by the stagnation which, in the opinion of some (see p. 1147), played such a vital role during the final dissolution.

Through the depression of the snowline, as the result probably in early stages of snowy, mild winters,[162] snow not wholly dissipated in summer was gradually heaped up in the innermost fastnesses of the mountains. Perennial snowfields, with new additions and increasing age, were compacted into ice and grew into ever enlarging glaciers, including those of the plateau type, as the snowline progressively sank. These crept down the valleys and swelled into confluent glaciers, amalgamating over the intervening spurs and water-

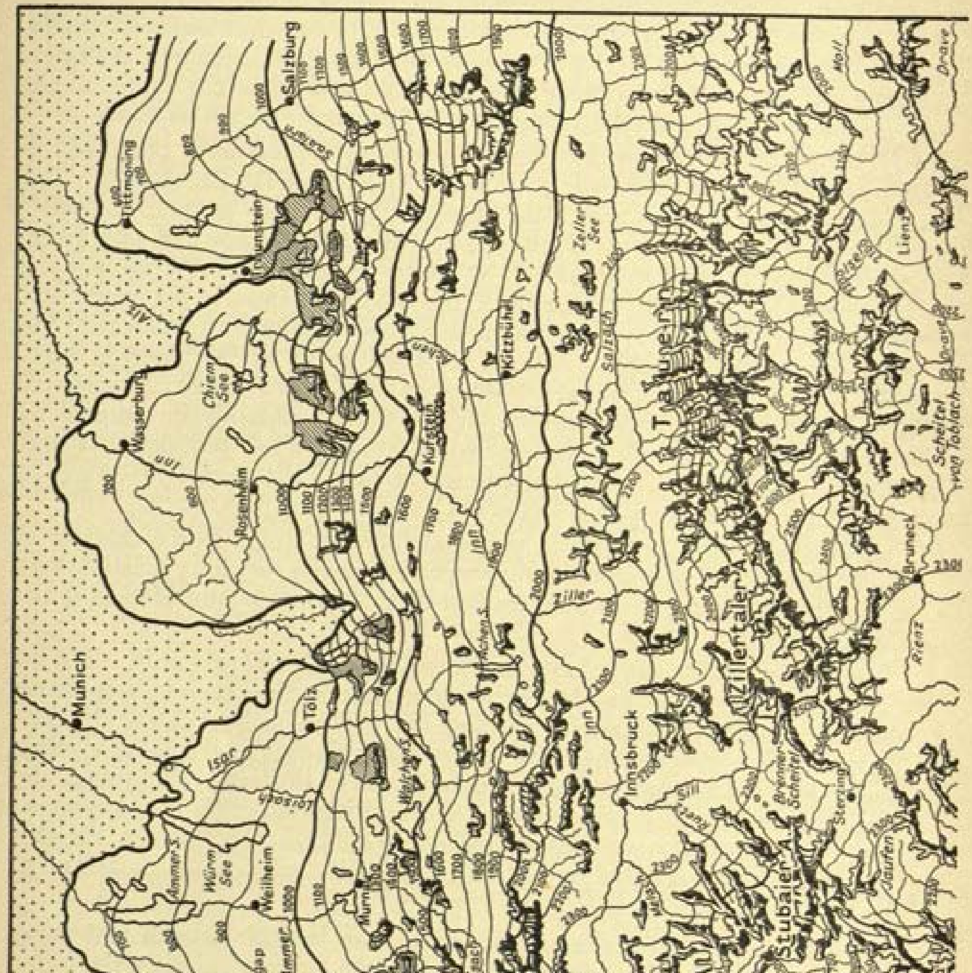
sheds, pushing out beyond the mountain fronts, and burying the surrounding plains. Interfering with each other's progress, they were deflected into lines which depended upon the relative mass and strength of their contributing elements. Reinforcement and congestion rapidly built up the piedmont masses and quickly extended the surface above the snowline where accumulation overbalanced loss. The advance became rapid. Ultimately, the brimming ice formed a "mountain ice-sheet" and arrived at the shores of the adjacent sea where it detached bergs which for a time checked its march.

There is as yet no means of deciding what time the growth consumed or whether it differed essentially from that required for the dissolution. The advance was doubtless spasmodic, temporarily or even generally rapid[163] (80–1000 m/annum ?[164]), especially when the falling snowline and rising surface brought large plateaux into the zone of nourishment[165] (see p. 654). The Elster ice-sheet may have advanced 100–120 m/annum in the neighbourhood of Leipzig.[166] From varves the annual advance in central Germany has been estimated at 600–800 m[167] and in Silesia at 120 m.[168] There is, however, no evidence that it was at any time catastrophic or reached the suggested figure of 6000–8000 m/annum.[169] It was almost certainly interrupted by recurring halts or even by extensive withdrawals. The "postglacial" stages (see p. 1159) were probably matched in the early Pleistocene by a crescendo series—the Günz may be the last of such a series (see p. 920).

The onset began in different places at different times, as for example in Turkestan,[170] and as is affirmed by supporters of sympathetic glaciations (see p. 677). Ice started to accumulate first on the highest mountains and in the far north.

At the climax, the general movement was outwards and seawards. The ice in its progress was guided by the grander features but, especially in much dissected country, suffered innumerable deviations which relief and the confluence and interference of the component glaciers and glacier-systems demanded; cross-striae and superimposed tills of different composition and origin indicate the debatable ground. The rising tide of the ice suppressed minor local centres or made them conform to the general movement, the flow being retarded or arrested on the iceward side but continuing unchecked to the lee.

Glacier types. The Pleistocene ice-masses in their growth and decay passed successively through most or all of the types of glaciers described previously (see ch. IV). Every type was present in Europe and North America from the initial snow-bank glacier to the vast ice-sheet of maximum glaciation. Countless examples might be cited in illustration. The reticular glaciers of to-day nowhere attain the development they did during the Pleistocene in the Sierra Nevada and Montana Front Range of North America and in the Alps[171]—contoured reconstructions of such glaciers have been made for the Karwendelgebirge,[172] for the Tyrol, Lugano and Tessin region,[173] for parts of the Bavarian Alps[174] and for the Etsch Glacier.[175] The Tagliamento Glacier of north Italy was a piedmont glacier,[176] as were those, including the Salzach, Inn, Isar, Lech and Rhine glaciers, north of the Alps. The Eigen and other glaciers of the Karawanken region were of the Turkestan type.[177] Expanded-foot glaciers occurred in north Italy, e.g. the Piave, and plateau glaciers were plentiful in the Limestone Alps[178] and occurred in central France[179] and on Boulder Mountain, Utah.[180] The Tatra's step structure


Munich
Salzburg
Rosenheim
Wasserburg
Landsberg
Kaufbeuren
Mindelheim
Weilheim
Tölz
Kufstein
Kitzbühel
Innsbruck
Lienz
Bruneck
Sterzing
Landeck
Chiem See
Würm See
Ammer S.
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Ziller
Salzach
Rienz
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Zillertaler A.
Stubaier A.

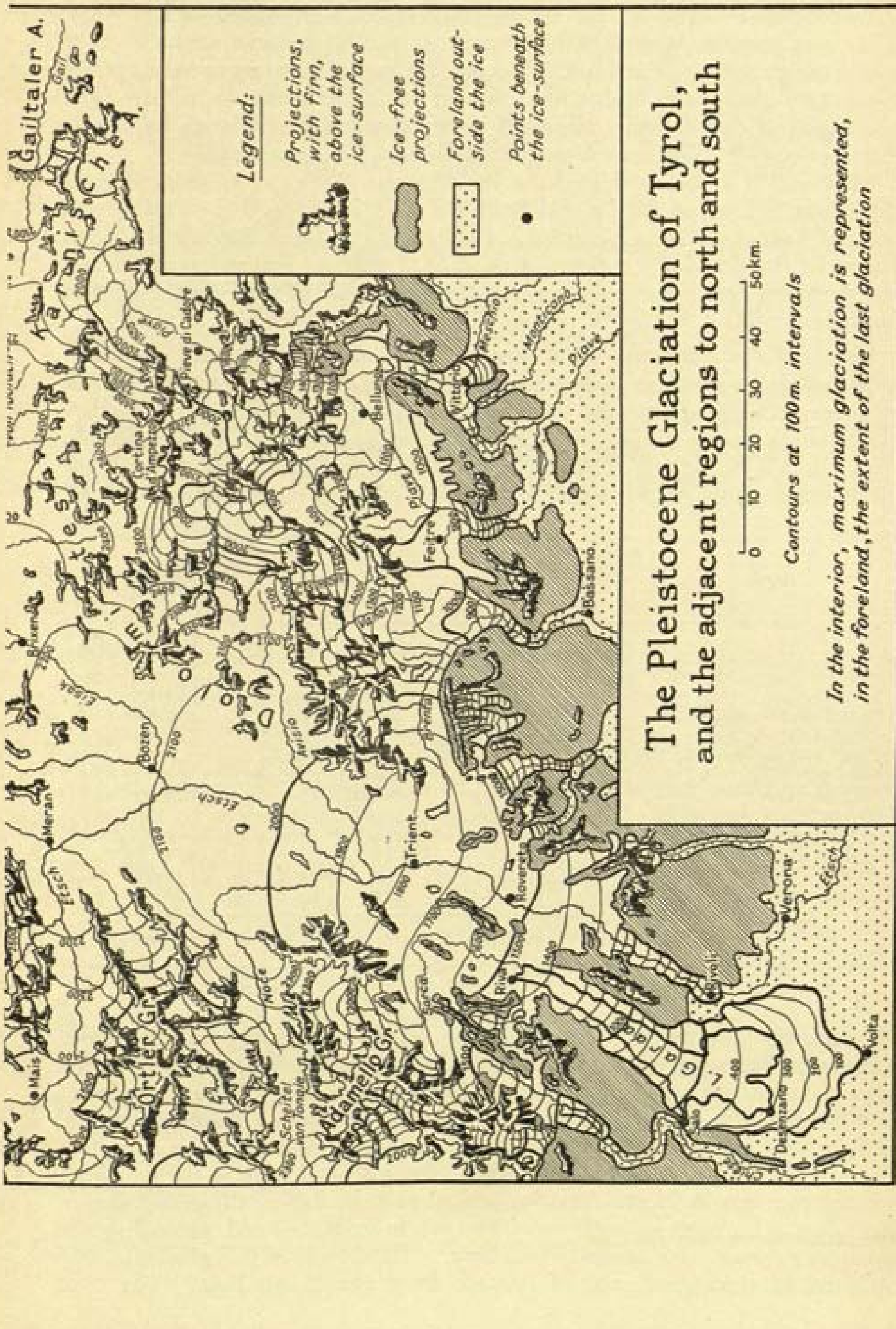


FIG. 124.—Contoured map of the Pleistocene ice of Tyrol. R. v. Klebelsberg, 911, p. 540.

caused a step-like recession of the ice, reconstructed glaciers marked by moraines forming on each step.[181] Moana Kea probably had a carapace.[182]

Parasitic glaciers existed in the Alps[183] and the Vosges[184] and have been suggested for east Lancashire where the Western Ice and Ribble Ice were confluent[185] and for the successive drifts of East Anglia (see p. 384). They may sometimes explain the lateral transport of material across a valley where the glacier-bed has none, or the occurrence of lateral moraines opposite a tributary glacier at a higher level than at any point above or below. The overriding of one Pleistocene glacier by another has been shown by erratic distributions.[186] Ice-slabs were general in lateglacial Sweden.[187]

Shelf-ice[188] probably skirted the Pacific coast of North America west of the Coast Ranges of Alaska and British Columbia, fringed the entire west coast of Vancouver Island, existed in Baffin Bay and Davis Strait and off east Labrador, bordered the entire east coast of Greenland and much of Iceland and lined Novaya Zemlya and part of the west coast of the South Island of New Zealand.

General distribution. The empire of the ice was vast and its sheets imprisoned large regions, especially where by the depression of the snowline wide surfaces moved into the nival climate. Its chill was felt over the entire globe (see p. 644), including the tropics,[189] for the snowline was depressed in New Guinea,[190] Ecuador[191] and Sierra Nevada de Santa Marta,[192] and the mean temperature was lowered 3–6°C or 8°C even in the East Indies.[193]

Region	*Surface-area million sq. km*			*Mean Thick-ness km*	*Volume million cu. km*			
	(*b*)	(*c*)	(*d*)	(*c*)	(*a*)	(*b*)	(*c*)	(*d*)
North Europe and west Siberia	3·3	13·0	10·2	1·05	37·7	5·0	13·65	11·4
East and south-east Siberia	} 3·3	3·2	1·5	0·8	4·8		2·56	0·5
Central Asia		0·5	1·5	0·4	0·36		0·24	0·5
Faeroes and Iceland, etc.		0·1	0·4	0·5	0·06		0·05	0·2
Greenland	2·0	3·0	2·3	1·4	6·3	2·7	4·2	3·5
North America	11·5	16·7	15·8	0·8–1·1	47·03	27·05	18·07	29·0
Temperate and tropical latitudes		2·4	0·1*	0·4	1·0		0·96	0·0*
Patagonia and Antarctic Islands		1·4	1·0†	0·7	2·5		0·98	0·4†
Antarctic continent	13·5	14·5	14·0‡	1·5	33·3	24·6	21·75	15·4‡
	33·6	54·8	46·8	1·1	133·05	59·7	62·46	60·9

* Australasia. † South America. ‡ Antarctica.

The present distribution of animals and plants and of birds in Haiti and Dominica also suggests a lowering.[194] Leaving aside the Antarctic ice, the glaciation was essentially periatlantic; for the flat basins of North America and Europe were favourable receptacles and the southern hemisphere offered little opportunity for greatly increased expansion. A map of the glaciation (fig. 125) shows that more than half of the glaciated area in the northern hemisphere was in North America and more than half of the remainder in north-west Europe, in both cases in middle latitudes and providing the greatest contrast with present conditions. The centre of this glaciation was situated in Greenland, 20° of latitude from the North Pole. The total

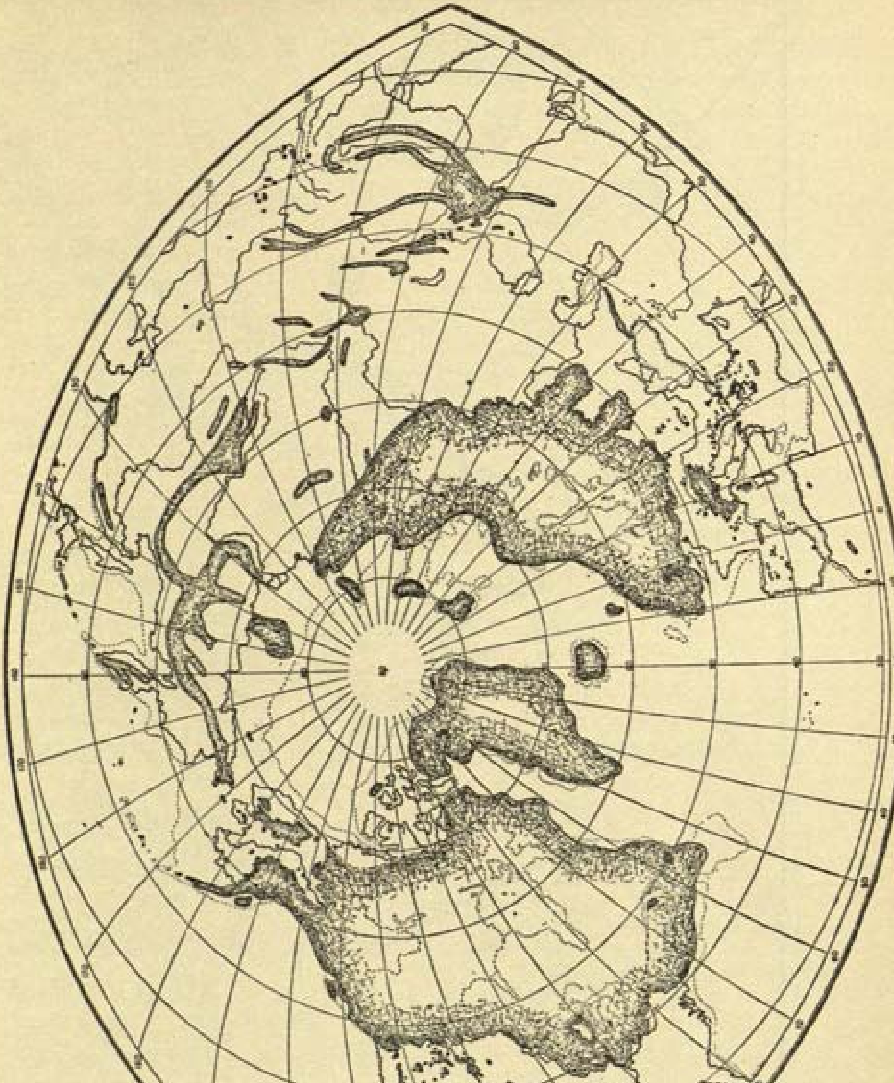
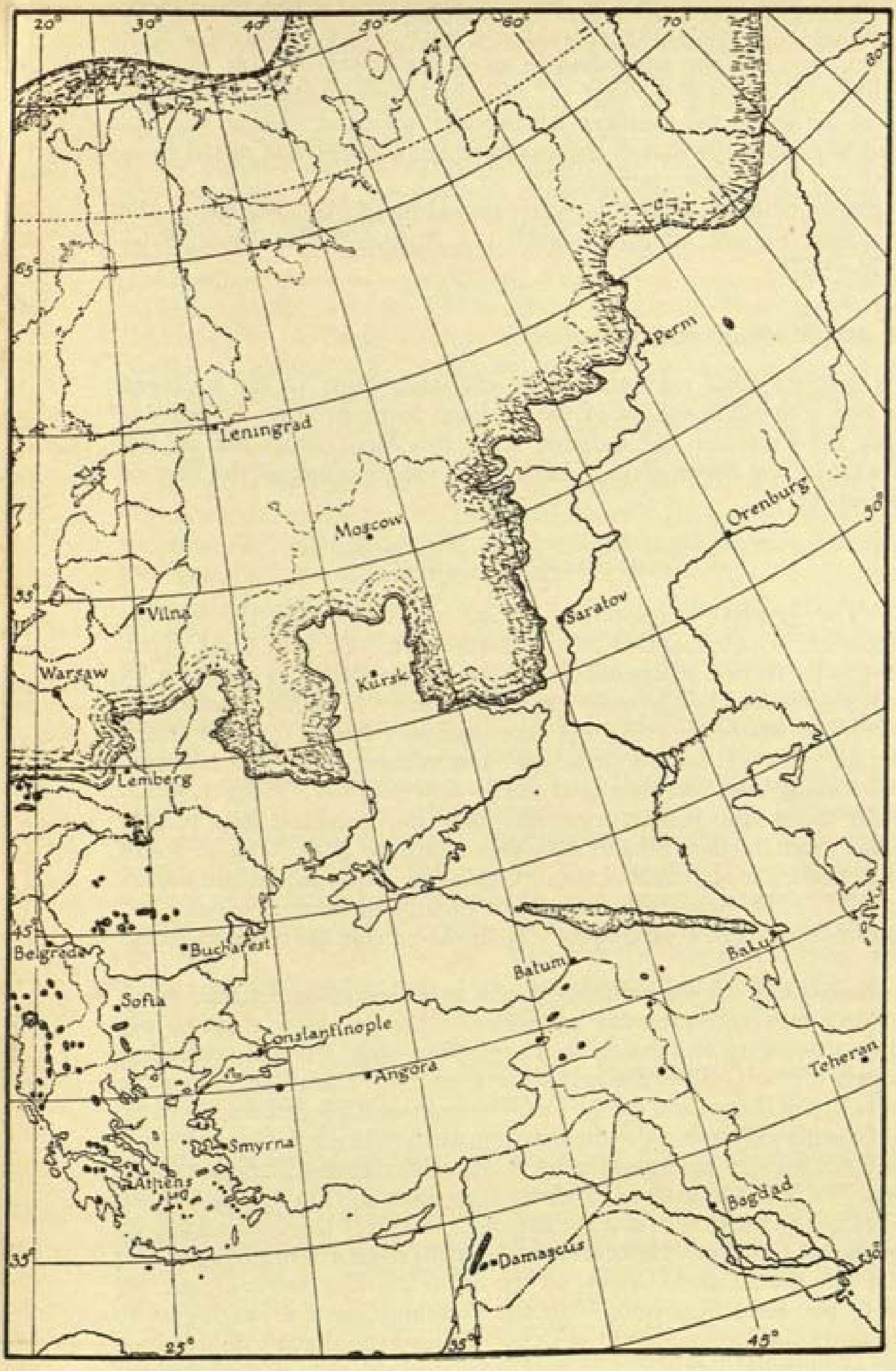


FIG. 125.—Map of Pleistocene glaciation in the northern hemisphere. Lambert's equal-area projection. E. Antevs, 67, p. 636, fig. 1.

FIG. 126.—Map of the European glaciation.



E. Antevs, 67, p. 660, figs. 11 and 12.

glaciated area, including Antarctica, is still uncertain—figures range from 30 to 55 million sq. km[195] or *c.* 30% of the land surface. Of this total, more than 11·5 million (= 3,670,000 sq. miles) lay in North America and more than 5–6·5 million (= 2,206,000 sq. miles) in northern Europe,[196] i.e. an oval 80° of meridian in length and about 15° of latitude in breadth. Hence the percentage of the ice in the southern hemisphere, which at present is *c.* 70, was reduced to *c.* 29 while that of the northern hemisphere was raised from 30 to 66 with *c.* 5 in the lower latitudes.[197]

The preceding table (p. 704) gives very approximately the amount of the ice in the various regions after Ramsay[198] (*a*), Antevs[199] (*b*), Penck[200] (*c*) and Valentin[201] (*d*).

2. Europe and Mediterranean Region

Europe's glaciers (fig. 126) nestled in the mountains of its southern peninsulas and within the valleys of the German Mittelgebirge. They deployed from the Pyrenees and radiated from the Alps, coalescing on the north and west on the Swiss Plain. In the north there occurred the Fennoscandian ice-sheet.

(*a*) *Fennoscandian Ice-sheet*

Extent. The greatest development of ice in Europe was the Fennoscandian ice-sheet which mantled all the north-west. Of very great depth (see p. 41), this ice flowed independently of the configuration, as is shown by striae and boulder-trains in Finland[202] and by striae[203] in south Scandinavia and north Norway where the relief was in control only during the later stages ("Fjord period"[204]). It buried the whole country except for a few marginal nunataks, including some in west and north-west Norway,[205] the Lofoten Islands[206] (as the erratic height, frost sculpture and botanical data testify) and, to judge from certain botanical evidence (see p. 965), even in south Norway, e.g. the tinds of Jotunheim and Galdhöpig (2468 m) on the watershed (Lat. 63° N.); H. Reusch[207] thought mountains in central Norway had only insignificant traces of glaciation. Kebnekaise was the only Swedish nunatak.[208]

The Fennoscandian ice was a mighty shield, strikingly asymmetrical: north and north-west radii were probably 200 miles (*c.* 320 km) long, those on the south and south-east up to 1300 miles (*c.* 2080 km) long. It was centred in the north part of the Gulf of Finland—the theoretical centre lay about the Stor-sjö in 14° 30′ E. Long. and 63° N. Lat.[209]—or in multiple centres like those of modern Greenland (see p. 75)—the maximum extent in north Germany was synchronous not with the maximum in north Scandinavia but with that of south Scandinavia.[210] With a surface of about 6,500,000 sq. km (2,145,000 sq. miles), it stretched east west over 4000 km and a diameter from Nordkapp to the Carpathians of 2500 km. Its ice streamed radially outwards in all directions; on the west into the Atlantic Ocean, on the north into the Arctic Ocean, on the east over the Kola Peninsula[211] to the Petschora, on the south-east to Kazan and down the Dnieper and the Don. It filled the shallow depressions of the Gulf of Bothnia, Baltic Sea, White Sea and North Sea, and on the east joined with the Ural and Timan ice, on the west with the British ice.

While it swept freely across the plains of Russia and Galicia on the east and

over the Low Countries on the west to the line of the Lower Rhine (Vogelenzang, Utrecht, Nijmegen)[212]—the Brabançon massif helped to bar its progress—the high barrier of the Carpathians and the German Mittelgebirge arrested it on the south. It pressed against their flanks to considerable heights (which may have been increased by subsequent tectonic movements[213]), namely, to 250–260 m in the Harz,[214] 300 m in the Teutoburger Wald,[215] 380 m in the Erzgebirge,[216] 337 m on Rummelberg[217] and elsewhere in the Sudetes[218] to 560–590 m (a figure of 750 m[219] was based on the relief), 700 m in the Eulengebirge[220]—the maximum height of the ice flood—550 m on Zobten,[221] 420 m on the northern slopes of the west Galician Carpathians[222] (the highest point is opposite the Vistula gap through the Polish middle mountains), 485 m on the Reichenstein Mountains,[223] and 450 m in the West Beskiden.[224] It thrust tongues up to 33 km long into the valleys,[225] e.g. the Neisse, Oder and the Carpathian valleys[226] (where in general it attained the 400 m contour and was 60–80 m thick at its margin) and swirled round the nunataks such as Zobten[227] (718 m), some of the Katzbach and Reichenstein summits,[228] and possibly over the quartzite ridge of Lysa Gora (611 m) in Poland.[229] Boulders and moraines show that it surmounted the main European watershed in the Moravian Gate[230] (*c.* 350 m) between the Oder and Beszwa (Elster glaciation), and carried into the March, a tributary of the Dniester, both debris and melt-waters.

Erratics and ice-flow. Its characteristic erratics or "indicator boulders", the subject of several important publications,[231] were in their general features worked out by the end of the 19th century. The igneous rocks include the granites of Småland, Wexiö, Stockholm, Åland (e.g. Ålandrapakivi) and the west Finland rapakivi, porphyries of Åland, Dalarne and Småland, and the red and brown Baltic porphyries, syenites (e.g. the Dalarne cancrinite syenite), basalts of Scania[232] and Åland, basalt tuffs from the floor of the southern Baltic and beneath Denmark and north-west Germany, and Oslo plutonics,[233] such as laurvikite, nordmarkite, laurdalite and rhomb porphyry. Their sedimentary members, which have been fully monographed[234] for Holland and Germany, embrace in their more than 300 types the Pre-Cambrian Dala sandstone, the Cambrian (Fucoid, Tiger and Scolithus sandstones), Gotland Silurian, Muschelkalk, Scanian Chalk, black flint, belemnites and sea-urchins, Danian sandstone, and Oligocene amber from the Baltic[235] which is distributed to Cromer, Schleswig-Holstein, Jutland, Westphalia, Silesia and Poland.

Erratics from Scandinavia are found in Denmark,[236] Heligoland[237] (rhomb porphyry, Elfdal porphyry, nordmarkite, laurvikite, Sarna aegerine syenite, rapakivi from Åland islands), Holland[238] and north-west Germany; from Gotland in East Prussia; from Finland and Lapland in north-west Russia[239]; and from Lake Ladoga in the Don region[240] (fig. 131). The distribution of the Scandinavian erratics has been frequently examined for the North German Plain,[241] and has been summarised for the eastern Baltic[242] and south-west Russia.[243] V. Milthers[244] has shown that those from Oslofjord and Langesundfjord are found in south-west Norway, and on the English coast from Yorkshire to Norfolk, owing to the Baltic Glacier pressing upon the eastern flank of the Norwegian ice whose westward displacement is also witnessed by the Åland granites in east Norfolk and the red Dalarne porphyry in east Yorkshire—Baltic and not Norwegian ice caused the maximum distribution of these erratics. Dutch erratics are mainly from the Baltic while

many Norwegian and west Scandinavian rocks occur at Hamburg and between the Elbe and Weser. The eastern limit of Norwegian erratics ran by Rostock, Neu Strehlitz, Eberswalde into Province Posen[245]: a rhomb porphyry erratic strayed as far east as Thorn.[246] The Baltic (not Sweden) contributed the bulk of the erratics north of the Sudetes and Carpathians, the percentage from that source rising to 85 in east Wolhynia and falling to 50 in Saxony.[247]

The influence of the Baltic depression was mainly confined to the earlier and later phases (see pp. 898, 943). At the maximum, i.e. during the Elster and Saale glaciations, the flow was radial[248] as is shown by the erratics and the course of the glacial limit across Europe, especially on the east and south, though it doubtless varied with the migrating iceshed[249] (see p. 670): in Denmark, the first movement was from Norway and the north, the second from the east (Dalecarlia–Baltic), the third from Norway. But E. Kummerow[250] has repeatedly maintained that the Baltic controlled the flow even during the maximum glaciation, notwithstanding the iceshed's migration

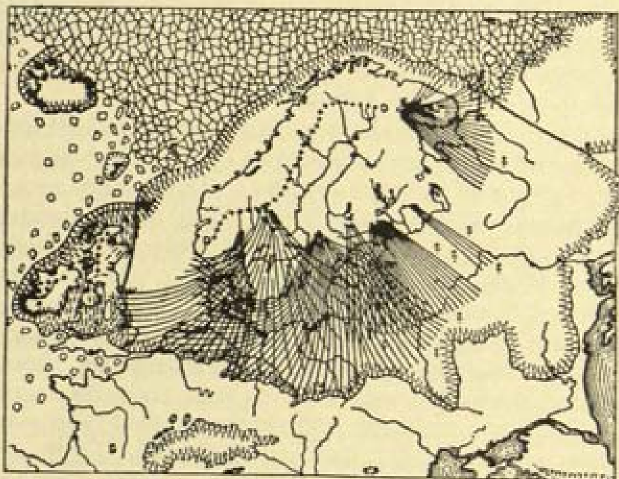


FIG. 127.—Map of some of the erratic fans of North Europe. Rhomb porphyry, Dalarna porphyry, Åland rapakivi granite, Kola Peninsula nepheline syenite. *1072* (2), p. 236.

and the tectonic movements. It gave the same drift composition from East Prussia to Holland and a boundary between the Norwegian and the Baltic ice that ran from Skagen to Sylt and Amrum. The Oder and Vistula lobes were lateral to the main stream.

North German rocks contributed their quota to the drifts: they include Cretaceous flints (derived from the parent rock or from *argile à silex*[251]), Jurassic rocks, Rüdersdorf Muschelkalk and quartzites from the Braunkohle.

Limits. The ice-calotte spread radially, as over north Germany[252] (east-west striae are local deflections[253]), to a terminal line which is not easy to define; for beyond the limit of continuous drift, distorted strata and striae, there are few erratics and some of these are indistinguishable from stream-borne boulders and (as in the Dnieper valley[254] where the 25-m terrace encloses them) may have been carried by drift-ice.[255] Its gravel patches,

when not intermixed with erratics, are difficult to distinguish from preglacial accumulations. Comminuted material went farther than recognisable rock-fragments. The mantle of loess in Germany and Russia and of alluvium in Holland, combined with subsequent erosion and weathering, has added to the difficulties.

The limit is composite and depicts the ice-edge at different epochs.[256] It is sometimes given by lake-deposits,[257] by outwash or moraines, as in Saxony and Holland,[258] or by anomalous drainage created by spillways or glacial diversions. It runs sinuously and irregularly, both vertically and horizontally, in accord with the preglacial relief. Crossing the Low Countries from the Hook of Holland by Rotterdam, Tiel and Nijmegen—the drift rises in the islands of Texel, Wieringen and Urk[259] and is proved by bores in the west[260]—it continues west of the Meuse (where terraces in North Brabant have been disturbed[261]) by Krefeld, Duisberg and Dortmund to the north-western edge of the Rhine-Westphalia mountains[262] so that northern erratics and drift occur in the Ruhr valley.[263] Glacial deposits are unknown in Belgium though Scandinavian erratics travelled as far south as the latitude of Brussels.[264]

The ice pressed against the wall of the German Mittelgebirge (see above) and thrust tongues into the valleys breaching them. It spread over the lower Harz Mountains to the northern slopes of the upper Harz, carrying its rocks deep into Thuringia and to the foot of the Frankenwald. It overrode the Teutoburger Wald, rested against the Thuringia Forest[265] and Fichtelgebirge,[266] attained the *Feuersteinlinie* in Saxony, and abutted upon the flanks of the Erzgebirge,[267] Riesengebirge[268] and Carpathians.[269]

The limit in Poland[270] and Russia is imperfectly known. Since Murchison[271] first sketched it, the Russian limit has frequently been re-drawn,[272] as by S. Nikitin[273] whose line, inserted in the International Geological Atlas of Europe (Feuilles F. III, IV, V, VI), lies within that assigned by the Russian Geological Survey in 1915 and by M. I. Dmtrijew in 1928 and S. A. Jakowleff in 1932.[274] It is sinuous and curves down the Don to 48° N. Lat. and down the Dnieper to 48° 40′ N. Lat.,[275] the most southerly points the Fennoscandian ice attained. The peninsular area of Kursk and the block of Voronesch between the two lobes remained free. The strong lobation of this ice about hills which are no more than 150 m high—the lobes are 500 km long—proves that this ice was not thick.[276] Farther east, the line probably crossed the Ural Mountains in *c.* 61° 30′ N. Lat., and east of these mountains ran from the locality of 59° 15′ N. Lat. 64° E. Long. north-eastwards across the Ob and Yenisei to Khatanga Bay.[277]

Terrain mixte. The northern drift was mixed with detritus from the south: a northerly carry from the Mittelgebirge had been recognised by C. F. Jasche for the Harz, by C. F. Naumann and B. Cotta for Saxony, by M. v. Orth for lower and middle Silesia, by F. Roemer for upper Silesia and by A. v. Dechen for Münster. Its importance was stressed by later geologists,[278] including Klockmann[279] whose development of the idea of a zone of mixed Diluvium skirting the mountains south of the Northern Drift found confirmation[280] in the Harz, Riesengebirge and Carpathians. In north Germany, this southern material which is especially abundant between the Elbe and Oder (fig. 128) and was doubtless contributed by preglacial and Pleistocene rivers, embraces quartz, quartzite, gneiss, Cretaceous sandstone, camptonite, leucite-basalt and nepheline basanite, together with andesitic

trachydolerite from Bohemia, phonolite and lamprophyre from Lausitz, and keratophyre from the Isergebirge.[281]

The Fennoscandian ice generated this mixed drift by incorporating southern debris with its own deposits, chiefly in the valleys, either by working over preglacial scree or terrace gravels (see p. 366) or by taking up detritus contemporaneously brought down by northward-flowing rivers[282] and their drift-ice.[283]

This *terrain mixte* has its maximum development in the Dutch *gemengd Diluvium* of Staring[284] which covers much of the provinces of Limburg,

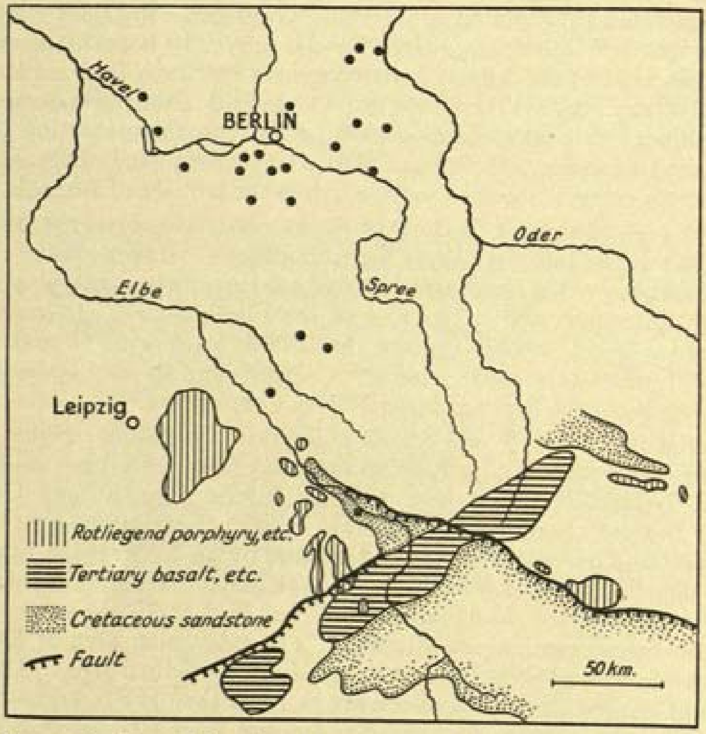


FIG. 128.—Map of the sites of boulders from the south in the north German drifts, with the probable sources. E. Kummerow, *G. Rd.* 30, 1939, p. 705, fig. 1.

Gelder, North Brabant, Utrecht and Overjssel. This Dutch drift contains Ardennes and other southern detritus of varied igneous and sedimentary origin[285] (slate, phyllite, quartzite, lydite, trachyte, andesite) and, as countless bores prove, grades downwards into a pure accumulation of southern and fluviatile origin,[286] Staring's *Rijn* and *Maas Diluvium*, which either underlies or merges insensibly northwards into Scandinavian drift.[287]

Shelf-seas. The encroaching Fennoscandian ice expelled the shelf-seas of west and north Europe, e.g. North Sea, Baltic Sea, White Sea and Barents Sea. Agassiz[288] early suggested that the North Sea basin was filled to the bottom with solid ice. British (see p. 631) and Scandinavian[289] geologists, following the lead of W. King[290] and J. Croll,[291] came to believe that the Scandinavian and British ice united over the North Sea into one vast sheet

(Lamplugh's East British Ice-sheet[292]) which was replenished by precipitation upon its surface[293] as well as by flow from the centre. Its slope is estimated at 12–13 ft/mile[294] (*c.* 1 in 420).

The ice-sheet is demonstrated by the pure Scandinavian drift at Warren House Gill, Co. Durham (see p. 749); by the geographical distribution of Scandinavian erratics in British drifts (fig. 129); and by the fanning of the

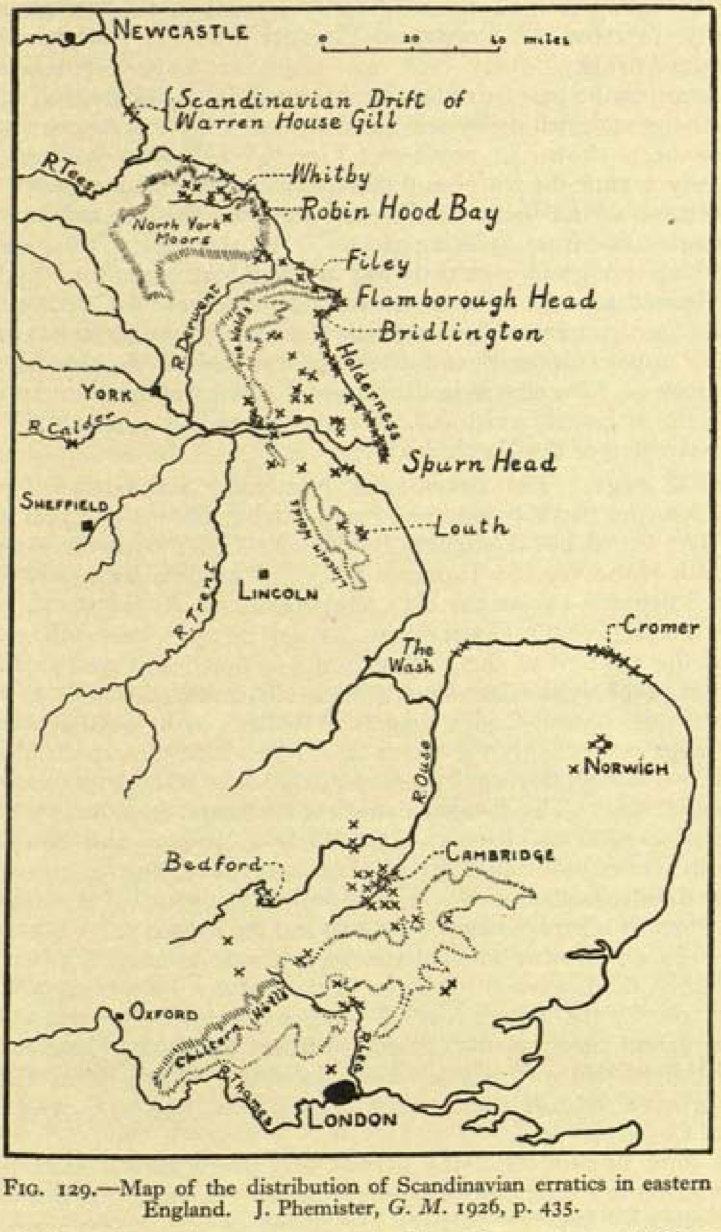


FIG. 129.—Map of the distribution of Scandinavian erratics in eastern England. J. Phemister, *G. M.* 1926, p. 435.

British glaciers along the east coast—the Tay, Grampian and Glenmore ice flowed northwards and passed over Caithness and the Orkney Islands, the Forth, Tweed, Tyne and Tees ice streamed southwards and expanded over

eastern England (see p. 749). This deflection is attributed usually to impact with the Scandinavian ice which proceeded from north to south as the ice grew[295] but occasionally to land extensions,[296] to earth-movements in the bed of the North Sea[297] or to shelf-[298] or drift-ice[299] which ferried Norwegian erratics to British shores.[300] Critics[301] of the ice-sheet hypothesis state that the gradient was too low to allow of ice-flow, that rocks from south-west Norway are unrepresented in British drifts, and that the Scandinavian ice was unable to cross the Norwegian Channel but was turned along this towards the Atlantic.

But a transmarine passage of this kind is possible[302] despite the high wastage by calving and melting by sea-water at even low temperatures: its feasibility has been shown in north-east Greenland[303] and in Ross Sea.[304] Islands may anchor the ice[305] and close pack-ice, as was postulated for the early glaciation of the Baltic Sea,[306] may minimise the loss and prevent the glacier or shelf-ice from breaking away.[307] By this means, ice-masses may become thick enough to urge their way across a basin or strait.[308] Growth was accelerated so soon as they touched the sea-floor; for circulating sea-water was then prevented from melting their base, precipitation took place upon their upper surface,[309] and discharge was curbed along restricted sea-fronts narrowing to straits, as in the case of the British Isles.[310] An isthmus at the Straits of Dover, which cut off warm waters from the south,[311] facilitated the crossing of the North Sea.

Seaward edge. The British and Norwegian ice extended into the Atlantic over the partially emerged continental shelf (see p. 1354) and was fringed by a broad but fluctuating border of pack-ice which was especially dense north of the Wyville-Thomson Ridge. The distance to which the ice penetrated depended upon the sea's temperature, as R. Hammer's observations on the Jakobshavn Glacier show, as well as upon its depth, since this governed the position of the calving-front: in north and west Scandinavia calving was probably the main source of loss and exceeded that by ablation.[312] Because of this control, Croll's suggestion[313] has usually been accepted, viz. that the edge was roughly the 100-fathom line where the rapidly deepening sea, modified though this was by a moderately lower ocean level (see p. 1354), facilitated calving. The distance doubtless fluctuated considerably along the 1500 miles (*c.* 2400 km) between Cape Clear in Ireland and Nordkapp in Norway and varied with the surface precipitation, the varying supply of ice from behind and the coastal relief.[314] Thus it probably protruded into deeper water off west Norway where the land was steep and the ice was thick but advanced much less far off Norway north of the Arctic Circle, as nunataks (see p. 965) and, possibly, the behaviour of the ice in the Lofoten Islands suggest. This was also true for the British coasts,[315] where the relatively warm waters and freer circulation encouraged melting, and where St. Kilda, 50 miles (80 km) west of Harris, had only a small local glaciation; North Rona, Sula Sgeir and the Flannal Islands north-west of Lewis were, however, overridden by mainland ice (see p. 753).

While some think the Lofoten Islands were overwhelmed from the mainland at maximum glaciation[316] (*Skjaergardstiden*[317]), others contend that they had nunataks,[318] like the Torngat Mountains on the opposite side of the Atlantic (see p. 1392), or had only a local glaciation,[319] joined on the east with mainland-ice[320] which flanked the islands to 300 m and glaciated the strandflat for a short time.

Confluence with Timan and British ice. The Fennoscandian ice was separate from all the peripheral ice-centres except those in Britain and the Timan mountains—the hypothesis[321] that the glaciers of the Faeroes and Scotland were united and covered a Scoto-Icelandic ridge has no foundation. It was confluent with the British ice on the bed of the North Sea and with the Timan ice between Mesen and Glasnow.[322] This ice was joined to that of the Ural Mountains[323] which harboured glaciers north of the source of the Petschora[324] (62° N.) but had few south of this and fewer still in the southern part[325] where U-valleys etc. have recently been found above 1000 m. According to the Great Soviet Atlas (1,1937, pl. 100) even much of the northern Urals, like parts of the Timan Mountains, are covered with eluvial clays and sands.

The Fennoscandian ice formed confocal hyperbolae, symmetrically disposed, at its confluence with the Timan ice[326] and with the British ice east of Scotland. The form of the hyperbolae, in these as in other cases—they marked the confluence of Highland and Southern Upland ice in Ayrshire (see p. 754), of Galloway and Cumbrian ice over the Solway (see p. 758), of Cumbrian and Pennine ice in the Vale of Eden,[327] of Scottish and Irish ice over Lough Neagh,[328] and of Galway and Leitrim ice in Co. Sligo[329]—depended upon the distance between the ice-centres and the strengths of the opposing masses[330]; since these varied from time to time, the shape of the hyperbolae varied as did the erratic distributions.[331] W. Ramsay[332] related the southward flow of the Fennoscandian ice south of the Baltic to the pressure the Timan and British ice exerted upon its flanks; the relative smallness of these local centres and the great distance between them make this suggestion most improbable.

(*b*) *Alpine Glaciation*

Of all the mountains of central Europe, the Alps experienced by far the severest glaciation. The present Alpine glaciers are indeed but the puny representatives of a gigantic *Eistromnetz* which during the Pleistocene choked the Alpine valleys, streamed out over the surrounding plains and covered altogether 150,000 sq. km[333] (fig. 134). The Rhône Glacier was 360 km long, the Inn Glacier 340 km, the Etsch 250 km and the Rhine and Drau each 200 km. The glaciers coalesced on the north in Bavaria and Württemberg to transgress the Rhine watershed and send their melt-waters into the Danube near Sigmaringen.[334] They deployed into Savoy on the west, and on the south descended as separate glaciers to the Plain of Lombardy, attaining a southernmost limit of 44° N.[335] Weissenstein, Lägern, Hörnli, Napf and other peaks and ridges projected as nunataks[336] up to 2500 m above the ice since, though its surface was generally domed and emergent ridges were more snow-clad than now, the firn basins remained separate, as Falsan[337] deduced from the angular Alpine blocks on the Jura flanks and others have confirmed for other reasons (see p. 644). Local centres existed in the North Limestone Alps, e.g. Schafberg, Höllengebirge, Traunstein and Sensengebirge.

The *Eistromnetz* was densest between upper Bavaria and the Italian lakes and became wider meshed to the west and to the east in which direction the piedmont glaciation diminished. East of the Enns and the meridian of 15° E. the glaciers remained within their valleys, spreading merely their fluvioglacial

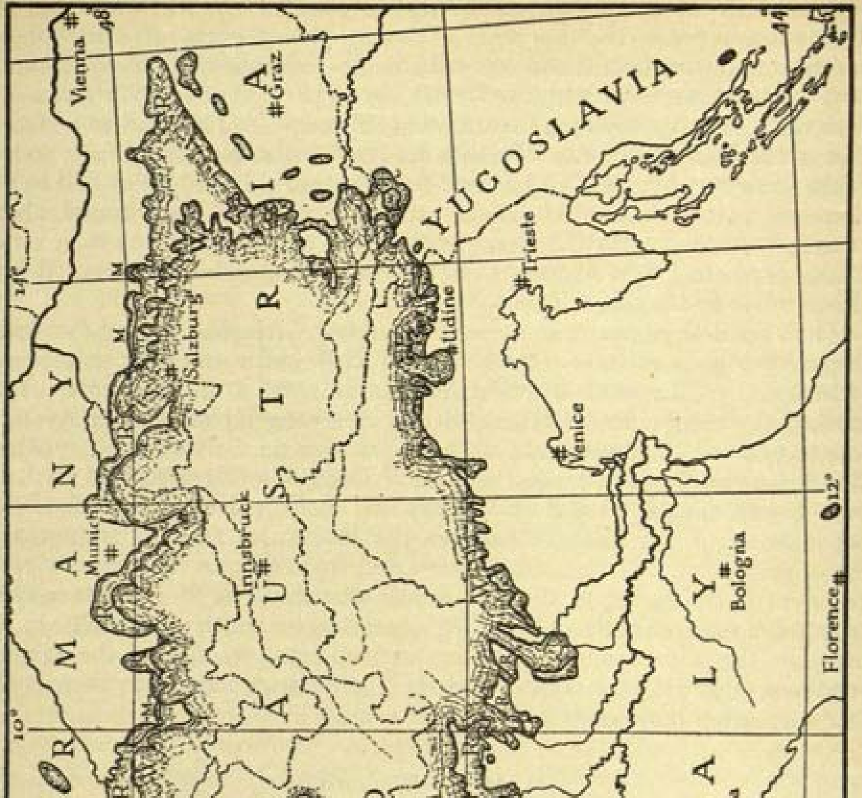


FIG. 130.—Map of the Alpine glaciations. M, R and W designate the Mindel, Riss and Würm glaciations. E. Antevs, 67, p. 681, fig. 16.

detritus upon the foreland: the Save Glacier ended near Radmannsdorf, the Drau near St. Paul, and the Mur near Judenburg. In the east, with the diminution in height and the rise of the snowline, the Alps were no longer completely glacierised but had separate centres with ice-free areas between them[338]—the ice in the Niedere Tauern, for example, was distinct from that of the Alps[339]—the extent in the different valleys depending upon their form. During the last glaciation, while the Traun and Salzach glaciers emerged, the Traisen, Erlaf, Ybbs, Enns, Steyr and Krems glaciers remained within the mountains.[340] The southern glaciers were also isolated, only two of them reaching the Po plain. This contrast with the northern slopes arose from climatic and orographic factors[341] and not from the presence of the sea in the Plain of Lombardy as conjectured.[342]

While the Rhine Glacier deployed freely, the Rhône Glacier, strengthened by the Arve Glacier and later by the Isère and Durance glaciers, was dammed up by the Jura Mountains and deflected to east and west; the gradient of its surface on the line Rhône valley–Chasseron (highest erratics on the Jura slopes) was only 2·5 ‰.[343] The ice rose so that the valleys were *übergletschert*[344] and completely overflowed a strip in the Juras, 70 km broad, and penetrated the passes into a further zone, hemming in the local ice (snowline 700–800 m) and compelling it to seek escape westwards.[345] In the west, the Rhône ice near Lyon was distant *c.* 90 km from the edge of the Alps and in the north the Inn Glacier at the northernmost extent of the Alpine ice was distant *c.* 80 km.[346] The Recurrence Phase or readvance of the local Jura glaciers on to ground vacated at the withdrawal of the Rhône Glacier[347] either did not exist[348] or was very small.[349]

The Swiss glaciers which attained a maximum of 63,760 sq. km[350] (of which 39,819 sq. km was in Switzerland itself) have been mapped for the successive epochs.[351] The classic works of Heim for the Swiss Alps,[352] of Penck for the Bavarian Alps,[353] and of Penck and Brückner for the Alps in general[354] are models of their kind.

(*c*) *Minor Ice-centres in Central Europe*

The minor ice-centres in central Europe constituted a ring of independent glaciations in the corridor between the Fennoscandian ice and the Alpine ice from the British Isles on the west to the ice on the Timan and Ural mountains on the east.

France. The glaciers of France, which Falsan[355] summarily described (with bibliography), lay, besides those of the Alps and Jura Mountains, in the Vosges and the Central Plateau—the supposed glacial phenomena in the Ardennes were apparently due to solifluxion.[356] The Central Plateau had plateau and valley glaciers,[357] and the flora of the Cevennes witnesses to the climatic deterioration.[358] The Vosges bore mountain glaciers, bigger on the west than on the east where the lowest ended about 200 m above the Rhine floor near Mülhausen and sent its outwash (Vosges Sand) into the valley as a series of cones which united into a low terrace. The glaciation of the central uplands, like that of present-day Norway, took the form of a thin, almost immobile *fjeld* ice.[359] The countless moraines and cirque-lakes of the Vosges were described about the middle of the last century by F. Leblanc, E. Renoir, H. Hogard and E. Collomb; more recent monographs[360] have

appeared on the glaciation of the various parts, including the Moselle region[361] which had a glacier 40 km long.

German Mittelgebirge. The German Mittelgebirge, whose former glaciation Agassiz recognised in 1841, lay mostly below the snowline, possibly because of their light precipitation and high evaporation.[362] Nevertheless, their glaciers were far bigger than those of the modern Alps[363] and diminished from west to east[364] with the rise of the snowline (see p. 651) and despite the increasing height of the mountains in that direction (Vosges 1423 m; Black Forest 1493 m; Riesengebirge 1603 m). The longest glacier in the Vosges measured 40 km, in the Riesengebirge, 5 km. Glacial traces are less marked in the Black Forest than in the Vosges, whence perhaps their later discovery (1862).[365] Their glaciers[366] were up to 9 km or even, it is said, 25 km long (Albtal), but remained within their valleys though their trains united with Alpine outwash in the Rhine rift valley. The northern Black Forest had either no glaciers or only cirque glaciers.[367]

The Sudetes, including the Riesengebirge, were examined by Partsch[368] who recognised a double glaciation, a later one of valley and cirque-glaciers and a snowline at 1350 m and an earlier plateau type (not undisputed[369]), distant 6·5 km from the Fennoscandian ice and with an area of 84·3 sq. km and a snowline at 1150 m. The Altvatergebirge, contrary to general opinion, may have nourished cirque-glaciers.[370] There were glaciers in the Swabian Alb,[371] Frankenwald,[372] Fichtelgebirge,[373] Bavarian Forest,[374] and up to 3 km long in the Bohemian Forest.[375]

The field evidence is often difficult to interpret and has led to many errors; creep has been diagnosed as glacial terminal curvature and slips as moraines. The supposed cirques and moraines of the Rhön[376] (950 m) do not exist[377] and the giant kettles and moraines of the Pfalz[378] are seemingly not genuine.[379] Similarly, the alleged glacial phenomena of the Erzgebirge[380] (1244 m) are solifluxion features[381] (excepting one cirque) and those of the Harz[382] (1142 m) have been thought to have no more substantial glacial foundation.[383] Glaciers in the Thuringia Forest[384] (984 m) are likewise repudiated[385] and the Odenwald, Spessart and Taunus were devoid of ice.

Carpathians. The Carpathians, now ice-free, had in accord with their lower elevation and more continental position and the easterly rise of the snowline (see p. 651) a much smaller glaciation than the Alps. There were glaciers in many parts of the Carpathians,[386] e.g. in the south and east and in the Radna, Litau and Transylvanian Alps.[387] Small cirque-glaciers occurred in the West Beskiden,[388] in the Niedere Tatra[389] (the glaciers, up to 7 km long, remained within the mountains) and in the Hohe Tatra[390] which had 21 glaciers totalling 266 sq. km, comprising cirque-glaciers on the north and piedmont glaciers, up to 14·2 km long, on the south. In the Radna Alps they were up to 6 km long, in the Transylvanian Alps 8 km.

(*d*) *Mediterranean Region*

Scattered glaciers existed around the Mediterranean, e.g. in the Pyrenees, Iberian Peninsula, Corsica, Apennines, Balkans, Asia Minor and the Atlas Mountains.

U-valleys, cirques, rock-basins, erratics and outwash sands attest the Pleistocene glaciation of the Pyrenees. First detected by Charpentier,[391] it has been the subject of numerous publications,[392] especially by Penck,[393]

and of a résumé by L. Carez.[394] The simple topography led to a simple glacier development as it does to-day. The snowline[395] was in the north between 1700 m and 1900 m, on the south at 2000 m and rose to 2200–2300 m in the east. The glaciers were separate and unconnected across cols. Like those of the present they were mainly on the north and in the centre of the chain[396]; the average length on the south was less than 30 km while on the north, where the ice descended 400–600 m lower, the Ariège Glacier was 63 km long, the Garonne Glacier 70 km and Lourdes had a foreland glaciation.[397]

Some of the highest elevations in the Iberian Peninsula had glaciers: Obermaier[398] has given a comprehensive account with map and references. Their small growth accorded with the behaviour of the snowline (see p. 652). Small hanging glaciers[399] lay in Cantabria, as in the Picos de Europa (2655 m), in the Sierra de Gredos (2592 m) and about Castanedo Lake, and the plateau type[400] occurred in the Sierra da Estrella, up to 13 km long, and up to 20 km long in Sanabria. Glaciers nestled in the cirques[401] of the Sierra de Guadarrama (2406 m), Sierra Nevada (3481 m), and Sierra Tejeda (2135 m; 36° 55′ N.) and in the mountains of Galicia (up to 2100 m). Portugal had 95 sq. km of ice.

There were glaciers on the peaks of the Apennines[402] which to-day, though covered with snow over large areas for three or more months, have only one small glacier, viz. the Calderone, near the highest part of the Gran Sasso (2914 m; 42° 28′ N.). They occurred in the Apuan Alps and in the Ligurian, Etruscan and Umbrian Apennines, in the Abruzzi and on Monte Pollino (39° 54′ N.), the southermost glaciated area. Every eminence above 2000 m in the central Apennines was glaciated; glaciers were up to 10 km long and 35 sq. km in area and even pushed out on to the foreland. The snowline[403] lay about 1670 m or at 1750–1800 m.

The most elevated parts of the Balkans had a local glaciation,[404] signs of which were first discovered in the Rila Mountains (2673 m) of the Rhodope massif by Cvijič[405] who did much to extend our knowledge of the Balkan glaciation.[406] Cirque-glaciers in the east gave place in the wetter west to valley or even to plateau glaciers, as in the Dinaric Alps.[407] Numerous glaciers rested in the Albanian cirques,[408] notably on eastern faces, though according to E. Nowack,[409] who summarised our knowledge of the Albanian glaciers, north Albania had plateau and valley glaciers up to 35 km long. Traces of glaciers have been seen in Dalmatia[410] and cirques in Macedonia[411] and in the Pindos and other mountains of south Greece,[412] as far south as 36° 55′ N., the glacier in this latitude on Taygetos being the southernmost in Pleistocene Europe.

A valley glaciation characterised Corsica[413]—the glaciers were up to 6 km long and existed in all mountains which were over 2000 m high. Cirque and hanging glaciers occurred in the Atlas Mountains[414] (4225 m; 32°–32° 30′ N.) in which evidence, more or less destroyed, has been followed down to 2100 or 2000 m. The highest summits of Crete[415] (2457 m) had no glaciation, nor seemingly had Etna[416] (3247 m)—the assertion that cirques existed on its north-eastern face at 1800 m[417] is said to be incompatible with the high level of the Mediterranean snowline (see p. 652) and with the Pleistocene age of the volcano (see p. 601).

The Caucasus[418] suffered from a glaciation intermediate in type between that of the Alps and the mountains of central Asia, though the claim that it

extended as a piedmont glaciation may be doubtful.[419] Its ice was not raised above the climatic snowline by orographic barriers as in the Alps but was confined to the valleys, leaving the plains and foothills ice-free. Its maximum was on the northern slopes of west and central Caucasus, the biggest glacier (Teberda Glacier) being 77 km long: the Terek Glacier was 72 km long, the Baksan 70 km, the Ardon 55 km and the Kuban more than 50 km.

Evidence of cirque-glaciers has been left behind in Asia Minor,[420] e.g. on the north face of Mount Olympus (2500 m), in Armenia including Mount Ararat (5160 m), on Demavend (5670 m) and other mountains in Persia,[421] and on some summits in Palestine[422] and Syria,[423] e.g. on Mount Lebanon (3066 m) and Mount Hermon (2819 m). Nevertheless, the climate was in no sense a cold one[424] since several animals, e.g. *Hyrax*, *Cervus dama*, *Panthera pardus* and *Crocuta*, survived, and the country had not a single cold-loving animal. Gebel Katharina (2541 m) in Sinai had a firn hollow.[425]

3. Asia

The extent of the Pleistocene glaciation in Asia, apart from the south-west just discussed, is still obscure. Its glaciers are known from the Himalayas, Pamirs, Hindu-Kush, and Kuen-lun and the great mountain chains of the interior and north-east. Recent maps,[426] which differ among themselves (see figs. 131, 132, 133, 191, 192), show a vast ice-expanse in both the interior and the north of the continent though much less than in the Fennoscandian and North American ice-sheets or the central Asiatic ice of P. A. Krapotkin.[427] The great west Siberian plain was covered with ice as were the hilly regions: the anticyclonic conditions favoured thinner ice than in Europe, with slower movement and less morainic material. The southern boundary lay in *c.* 60° N. Lat., as against *c.* 50° in Europe and *c.* 40° in North America, and coincided roughly with the present zero-isotherm, though in Europe and North America the ice-edge lay 10–20° south of this isotherm. The disjunct floral and faunal distributions in Eurasia (see p. 1382) also prove extensive glaciation.[428] Nevertheless, the ice, though extensive—the Siberian ice-sheet covered *c.* 4 million sq. km[429]—was probably relatively thin: measured on the flank of the Urals it was *c.* 700 m thick[430] (see below).

The Himalayan glaciers, as Hooker[431] first noticed, are mere vestiges of the former giants[432] which existed for example in the Everest Range[433] and debouched upon the plain of Kashmir.[434] They were more extensive in the Pamirs[435]—the Muksee Glacier was *c.* 195 km long—and considerably developed in Tibet[436] and the Karakoram Mountains.[437] A powerful glaciation centred in west Kuen-lun[438] and glaciers up to 100 km long occupied the valleys in central Kuen-lun[439]: they extended into the Tarim basin. Plateau glaciers occurred in Kitschik-Alai[440] and with valley and cirque-glaciers in Tien-shan.[441] They have also been discovered in Nan-shan,[442] in Outer Mongolia[443] and Altai,[444] the largest attaining great lengths, such as the 320 km of the Tschulyschmanby Glacier in east Altai, the 150 km of the Buch Glacier in south Altai, and the 340 km of the Katun Glacier in central Altai. Central Kurdistan also had a mountain glaciation.[445]

The Ice Age had seemingly little effect in south-east Asia. Yet bighorn sheep in Shantung may indicate an Alpine climate[446] and glaciers apparently existed in the mountains of China.[447] Cirque-glaciers were present in south-

west China, in Wutai-shan and Taipau-shan, and in west China and Yunnan. Certain features (striae, U-valleys, boulder-clay, moraines) have been held to indicate valley glaciers in the Yangtze-kiang valley[448] in 29° 30′–37′ N., though these would seem to be doubtful and out of harmony with all other glacial relationships—they require a fall of the snowline of

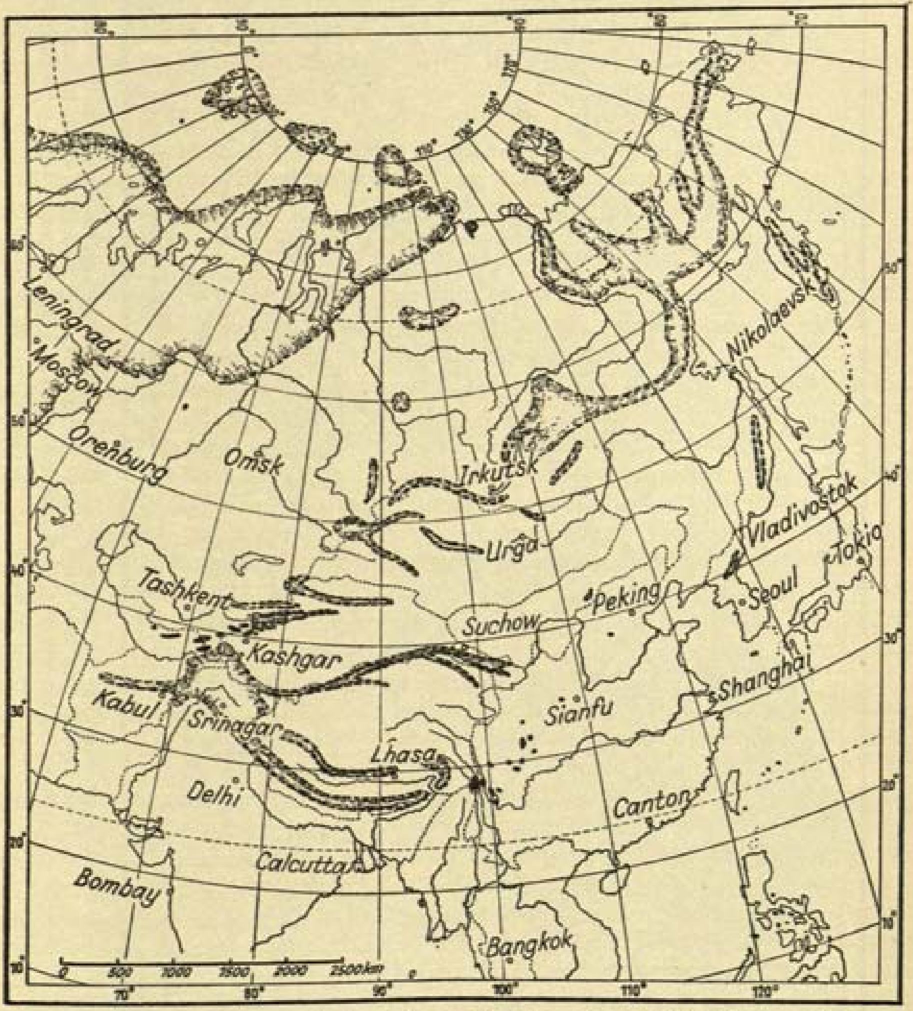


FIG. 131.—Map of the glaciation of Asia. E. Antevs, 67, pp. 688, 689, figs. 18, 19.

2000 m. The so-called glacial deposits were probably solifluxion products of a colder and wetter climate.[449]

Glacial signs have been known for many years from the north coast of Siberia[450]; they include moraines in the lower Ob, striae from the mouth of the Yenisei, and striae and moraines in the Taimyr Peninsula. They were referred to a weak glaciation (e.g. A. v. Bunge thought that the *c.* 1800 m high Verkhoyansk Mountains were ice-free) or to river-ice.[451] Recent research has shown that the glaciated valleys, cirques, striae, erratics, moraines and

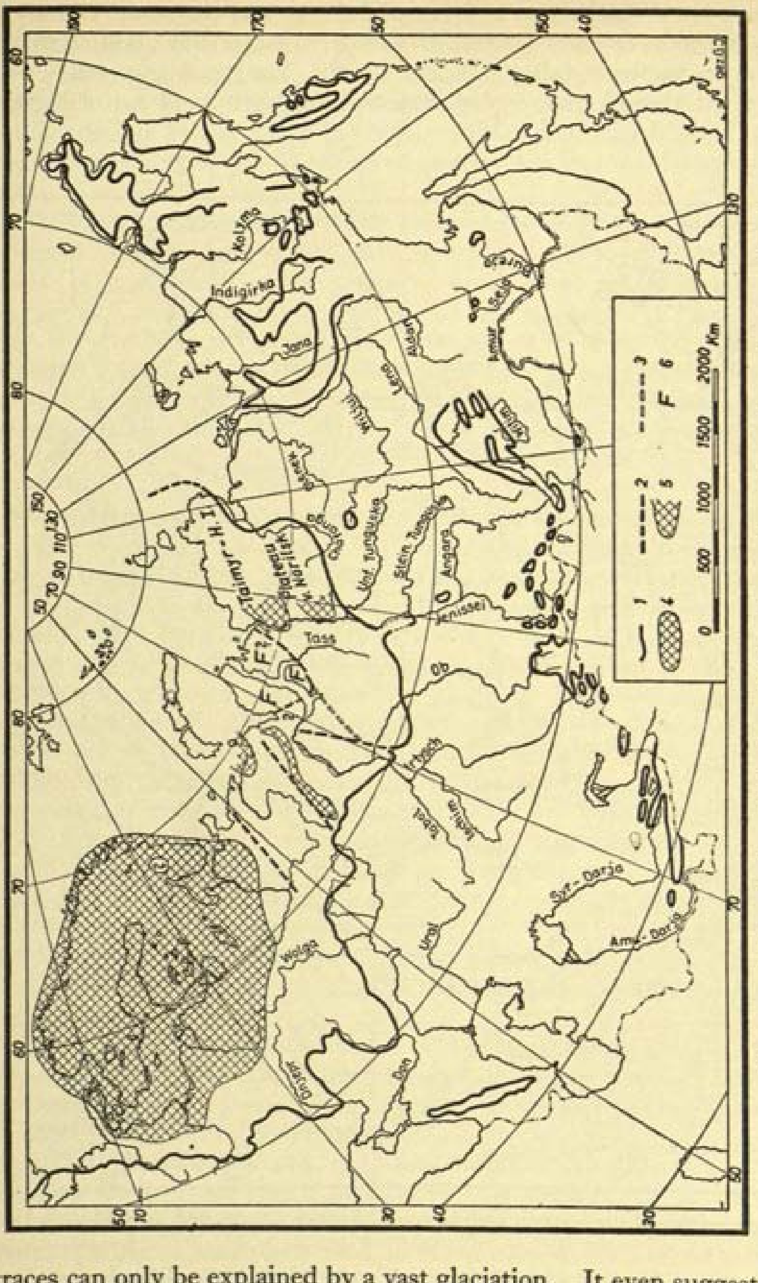


FIG. 132.—Map of the glaciation of Siberia. 1, boundary of maximum glaciation; 2, boundary between individual glacier-regions; 3, eastern boundary of Ural glaciation; 4, extent of last glaciation; 5, ditto partially known; 6, ice-free areas. *1695*, p. 18 (map 2).

terraces can only be explained by a vast glaciation. It even suggests that ice extended from the Urals to the Pacific coast north of the 62nd Parallel[452] and that vast glacier-lakes, stretching over the west Siberian plain from the Urals to the Yenisei and Ob (ice-lake sediments are known in this valley), drained southwards to the Aralo-Caspian Sea[453] by the Turgai depression. However that may be (and it is seriously disputed[454]) there can be no doubt, despite our imperfect knowledge, that with Obrutschew[455] we must abandon the view of a feeble Siberian glaciation originally affirmed by A. Woeikof[456]

and generally accepted because the extreme winter cold was deemed unfavourable. Nevertheless, it would seem that the ice was thinner than in Europe and that the subglacial relief exerted a greater influence[457]—the highest mountains of the northern Ural Mountains were nunataks at maximum.

Many centres of radiation, closely connected with high land, were simultaneously active, with coalescing glaciers spreading in all directions[458]: every glaciated lowland is continuous with such a centre (fig. 132). The more important lay in the Ural Mountains, in the peninsulas of Yalmal and Gyda which glaciated the Ob and Yenisei, and in Taimyrland and the vast rolling upland between the Yenisei and the Lena. Every mountain east of the Lena, e.g. Verykhoyansk[459] and Stanovoi,[460] had plateau and valley glaciers which swept into the basins of the Yana, Indigirka and Kolyma rivers as far as the New Siberian Islands.[461] The western half of the Taimyr Peninsula was overridden by ice 400 m thick from centres in the Byrranga Mountains or even in the Nordenskiöld archipelago and Severnaya Zemlya[462] which moved southwards to Anabar Bay and the Yenisei[463] and to 64° or even 60° N.[464] Ice from Novaya Zemlya crossed Timan, and its southern boundary between the Ural Mountains and Irtysh lay in 61° 30′ N. Lat., and east of Irtysh lay in 60° N. and crossed the middle Chatanga.[465] Chelyuskin Peninsula was enveloped though Jamal Peninsula and probably also Gydan Peninsula were ice-free,[466] as well as much of the coast of Indigirka, Yana and Kolyma. A mass of ice on the Siberian continental shelf or a downfaulted land to the north, forming part of a circumpolar cap, has been postulated.[467]

In Wjatka and Kama erratics are from Novaya Zemlya and the Ural Mountains, while in the upper Petschora they came from the former only.[468] Because of the ice from Novaya Zemlya and the steepening of the eastern slopes of the Ural Mountains, the Ural ice reached the lower Ob, i.e. a distance of *c.* 500 km, though on the west it only attained the foot of the mountains[469]—its total area was *c.* 800,000 sq. km.

The Vitim Plateau and other highlands east of Lake Baikal,[470] as well as the East Sayan Mountains,[471] were severely glaciated though the extent is unknown. Only corrie and small valley glaciers existed in the Baikal mountains.[472] North-east Siberia, including Sakhalin, was glaciated[473] (fig. 133), though much is still to explore. There was a mountain glaciation, with valley, plateau and piedmont glaciers. Ice was centred on the Verkhoyansk, Chersky, Kongin, Kolyma, Anui and Anadyr mountains and coalesced into an ice-sheet extending from the Lena to Bering Sea. Independent centres occurred on Koryak Mountains and on Kamchatka. Wrangel Island and the New Siberian Islands had small centres,[474] Wrangel Island even during the last glaciation. The Sikhota Alin and Chans-pai-Shan, north and south respectively of Vladivostock, also bore glaciers.[475] The Tschuksch Peninsula was almost entirely buried by ice.[476] Typical glacial features (cirques, U-valleys, moraines) are to be found in Kamchatka[477]; glaciers flowed down the eastern slopes nearly to the sea but left a belt, 60–100 km broad, uncovered on the west and allowed woods of *Betula ermani* to survive. Reticular glaciers in central Kamchatka gave place to cirque glaciers farther south.

Cirques, striae and moraines demonstrate the glaciation of the highest summits of Japan[478] and a snowline[479] at 2800–3000 m which fell northwards to 2550 m. This is in keeping with the fall in temperature of 6°C suggested by fossil plants[480] and by the evidence of the corals[481] and molluscs[482] but

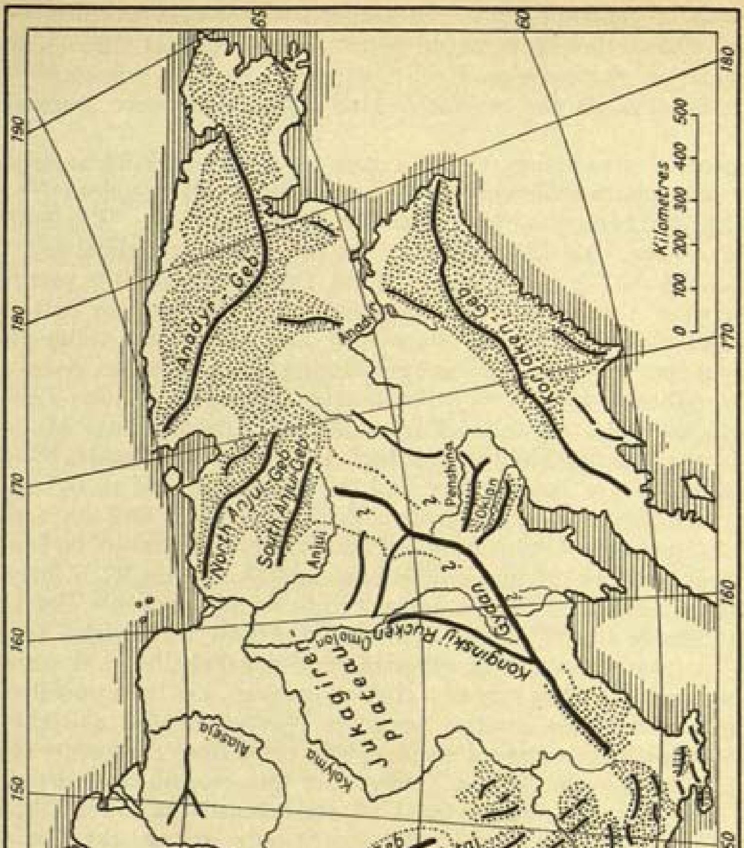


FIG. 133.—Map of the glaciation of north-east Siberia. E. Thiel, *1695*, p. 23.

difficult to reconcile with the statement (based possibly on insufficient evidence) that the corals denote a warmer climate[483] due to the closing of the Bering Strait.[484] The glaciation was in any case trivial: glaciers were very limited in extent; cirques are only slightly concave; and fluviatile topography

is dominant. Formosa which was the southernmost centre in Eurasia (23° 27′ N.) had small cirque glaciers[485]—the snowline was at 3400–3500 m—as had the Seturei Range (2554 m) and Shan Alin (above 2440 m) in Korea.[486]

4. Arctic and Subarctic Islands

Arctic latitudes which escaped the Permo-Carboniferous glaciation were for the first time deeply glaciated during the Pleistocene. Spitsbergen[487] was in the grip of a vastly bigger glaciation than to-day. U-valleys, rounded nunataks, striae, erratics and moraines prove this abundantly though epi-glacial movements of the land and sea have largely destroyed the signs on the lower terrain.[488] Ice from a more severely glacierised North-East Land[489] filled Stor Fjord and overrode Barents Island in its southerly passage.[490] On the north, it poured into the sea, its marginal moraines building up plateaux off the coast.[491] Farther west[492] the ice, 1000 m thicker than now, left free only the highest summits and soundings reveal submarine moraines on the continental shelf.

Novaya Zemlya experienced a severer glaciation which T. Tschernyschew[493] noted and others have amply confirmed.[494] The ice, burying the two islands up to 1100 m, built a shelf on the west and flowed far into Barents Sea with a maximum thickness of 700–1000 m in the coastal strip. Its influence may have been felt as far away as Franz Josef Land,[495] north of the Timan Mountains, and in north Siberia.[496] Franz Josef Land had more ice than now[497] and Bear Island (536 m) a radiating ice-cap.[498]

The extent of the ice in Barents Sea is not certainly known. It is possible that a landmass on this site subsided in Mindel time[499] and that ice from north Russia, east Spitsbergen, Novaya Zemlya and Franz Josef Land united in one sheet over the shallow Barents Sea[500] (G. De Geer[501] suggested a glaciation of Spitsbergen from a point in the sea to the east). This agrees with easterly ice-scratches found on Bear Island,[502] with boulders from the Ural and Timan ice discovered as far west as the Kanin Peninsula, with fossiliferous blocks, identical with those of the Timan Mountains, seen on Kolguev Island[503] (which consists exclusively of glacial and marine deposits[504]); and with the depressions in the bottom of Barents Sea, interpreted as ice-eroded hollows.[505] The unconvincing nature of some of this evidence (drift-ice, for example, may have carried the blocks as they probably did those on King Charles Land[506]), together with the relative smallness of the surrounding land and the power of the sea to break up glacier-ice, make it more likely that glaciers occupied only the part between Kola Peninsula, Novaya Zemyla and U.S.S.R., the rest being sheeted with pack-ice.[507]

It is reasonably certain that a small independent ice-cap[508] covered the whole of Iceland though an ice-free southern part has been postulated.[509] The Faeroes,[510] excepting the highest summits, were likewise buried by local ice, possibly 500 m thick, which streamed outwards to the coast—foreign erratics are missing save on the shore where they may be ship's ballast (F. Zirkel) or the discarded burden of drift-ice.[511] Failure to find on Beerenberg (2545 m) any evidence of glaciation, apart from that at present in progress, has led to the tentative conclusion that Jan Mayen, which originated entirely by volcanic processes, came into existence in post-Pleistocene time.[512]

Greenland's *Yderland*, despite assertions to the contrary,[513] bears countless

proofs of a bigger glaciation[514]; rounded summits, erratics up to 1800 m and several hundred metres above the existing ice in north-east Greenland at distances 40 or 50 miles (*c.* 65–80 km) from its edge; drift, relatively thin and scarce; and striae up to 1200 m A.S.L. on islands and peninsulas now bare of ice in south-west Greenland—all attest this. The ice, on an average perhaps 150 m thicker,[515] reached beyond the coast over much of east Greenland, overwhelming islands and peninsulas,[516] and even depositing its moraine

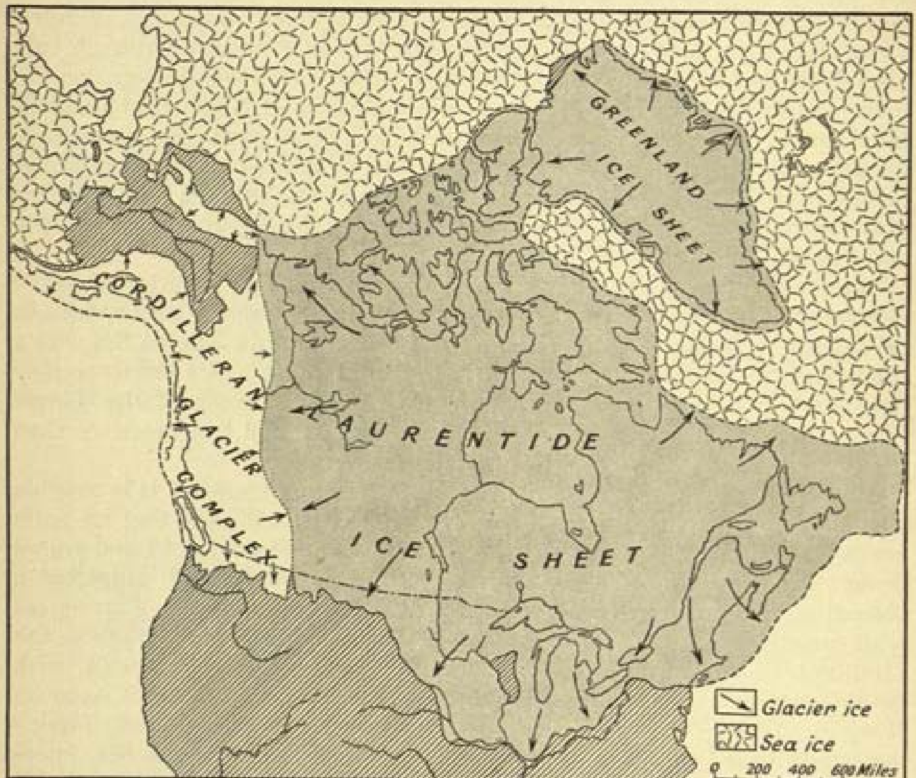


FIG. 134.—Map of the North American ice-sheet. R. F. Flint in C. O. Dunbar, *Historical Geology*, 1949, p. 439, fig. 282.

as submarine banks.[517] In parts of west Greenland, the ice once extended seawards over the entire landmass[518]: it may have been continuous with the ice of northern Labrador[519] (see p. 729).

The flow was generally directed to the coasts and parallel with the fjords. Nunataks, distinguished by their sharp alpine silhouettes (see p. 576), and unglaciated strips existed in east Greenland[520] and in west Greenland,[521] as in 66° N. and 77–78° N. They mainly occurred in south Greenland,[522] especially along the east coast from Cape Farewell to Angmagsalik and in the districts of granite and gneiss; a map of the alpine topography in south-west Greenland[523] is very instructive. North Greenland was completely covered except for such nunataks as the Devil's Thumb and the northern half of Peary Land whose vast belt of terminal moraine, up to 45 m high and 5 km broad, bounds the glaciated country on the north.[524]

5. North America

(a) North American Ice-sheet

Extent. The North American ice-sheet was immense (fig. 134): its literature, surveyed from time to time,[525] is of comparable proportions. Ice concealed more than half the continent, including the whole of Canada, less the Yukon territory[526] and part of Labrador (see below). It overwhelmed most of the north-east of the U.S.A. and extended down the Atlantic coast to central New Jersey and on the Pacific coast to Cape Flattery in northern Washington[527]—Long Island, Martha's Vineyard and other islands as well as Cape Cod consist largely of drift resting on submerged banks. It overrode, even during the Wisconsin stage, the White Mountains[528] (6293 ft: 1918 m), Catskill Mountains[529] (4205 ft: 1282 m), and Mount Katahdin[530] (5150 ft: 1570 m) in Maine, its margin spreading in a great curve as far as the valleys of the Missouri and Ohio (it crossed this river into Kentucky near Cincinnati and at points below[531]) and to St. Louis on the Mississippi, more than 2000 km from the Labradorean ice-centre. Its southern limit ran through New York, New Jersey, Pennsylvania, Ohio and Indiana, to its lowest latitude of 37° 35′ in Illinois (ice-rafted boulders in the Mississippi are strewn as far as 37° 11′[532]) where the present meteorological and topographical conditions are least favourable[533]—this southerly expansion was owing to the resistance offered by the great mountain barrier towards New England and New York, to moisture-bearing winds from the Gulf of Mexico (see p. 661) or to anticyclonic winds which, blowing in from the North Atlantic, brought more moisture and a richer vegetation than on the opposite side of the ocean.[534] West of the Mississippi, the margin followed generally the course of the Missouri, though it crossed this valley in places in North Dakota to a distance of 20–60 miles (*c.* 33–97 km) and to a less amount in South Dakota[535] (see p. 496).

The ice enclosed the Driftless Area[536] of Wisconsin, north-west Illinois, and south-east Minnesota (not Iowa as earlier thought) which comprised over 10,000 sq. miles (26,000 sq. km) of pre-Cambrian and Lower Palaeozoic rocks. This ice-free area, first detected by J. D. Whitney,[537] is clearly delineated along the Wisconsin drift border, though its boundaries are less certain where the older drifts have been seriously dissected or obscured by loess. It owed its freedom from ice to its situation between the Labradorean and Keewatin ice-sheets, to the obstructing highlands of north Wisconsin (600 m higher than the lake basins) and to the readier flow along the great Michigan basin and the low land the Red and Minnesota rivers drain.[538] The fingers of the *mer de glace* differed in age on the east (Lake Michigan lobe) and west (Des Moines lobe) and therefore never wholly encompassed the region or isolated it from the continuous ice-free country to the south, although the drift sheets overlap and at the Illinoian stage the ice advanced more than 300 miles (*c.* 480 km) to the south. They blocked the valleys, flooded the margins,[539] as in glacial "Lake Wisconsin" on the eastern fringe, and rafted erratics along the depressions that dissect it. The area, invaded by wind-blown dust (loess) and outwash from the pre-Wisconsin ice-sheets[540] was subject to periglacial weathering[541]—"fossil" blockfields, etc., occur—and may have possessed local snow-drifts or glaciers.[542] Another driftless area occupied 300 sq. miles (*c.* 780 sq. km) on the international boundary in south Saskatschewan.[543]

In the east, the ice passed off the coast of Maine and Massachusetts—the shoals and big submarine banks near Cape Cod and Nantucket Island, in the Gulf of Maine and at the end of the submerged Hudson River Channel may be its terminal moraine,[544] for till has been found on Georges Bank.[545] Between Long Island and Newfoundland, the ice may have spread out over a 1000 mile (*c.* 1600 km) front as a mass of shelf-ice, and a row of banks, probably the terminal moraine of the Wisconsin ice, with a core of rock, extends along the greater part of the Labrador coast.[546] Encircling marginal nunataks,[547] the ice crossed the international boundary in the Maritime Provinces of Canada and transgressed the boundary as a number of marginal lobes in the meridional valleys of the Cordilleran ice-sheet to 48° 20′ N.[548] where the dry climate arrested the advance. Impinging against the northern face of Gaspé Peninsula to *c.* 300 m, it swept along Chaleur Bay on the south, leaving part of the peninsula unglaciated[549] though crowned by local cirque glaciers[550] (see p. 1392)—even the Shickshock Mountains (4350 ft: 1326 m) were overridden by fairly clean Labrador ice.[551] Contrary to an earlier view,[552] the ice moved southwards over Nova Scotia, the Bay of Fundy and the Banks[553]—the Bay of Fundy, probably a fault trough,[554] has been interpreted as a fjord bounded by glacially eroded escarpments.[555] The irregular terminal line of the extremely thin ice coincided approximately with the eastern and south-eastern shores of Cape Breton Island[556] (which had an independent ice-cap[557]), while the ice overrode the lower ground of Prince Edward Island[558] (contrary to earlier opinion[559]) and (doubtfully), the Magdalen Islands[560] which some have thought were unglaciated.[561] Anticosti and the Mingan Islands of Quebec were at one time overridden and received their "preglacial flora" by later immigration from Newfoundland and Gaspé Peninsula.[562] The big submerged moraine stretching from the Strait of Belle Isle to the junction of the Anticosti and Newfoundland channels probably marks the front of the last ice-sheet.[563]

It is averred[564] that the ice failed to reach the sea in the Torngat region of Labrador and that the sharply serrated peaks, about 2100 m high and mantled with disintegrated rock, were persistent nunataks. Nevertheless, a great ice-flood seems to have proceeded along the many long, graded "through valleys" to the sea and to have overwhelmed the whole country at maximum glaciation in accord with the existence of small glaciers in the recesses of the mountains, of widespread moutonnée and ice-polished forms on the higher summits of the Central Range up to *c.* 1400 m, and of U-shaped cols at considerable altitudes.[565] Local ice-fields, like those of modern Grinnell Land, probably covered many areas which the main ice-mass left free.[566] The endemic plants (see p. 1392) characterise particular distributions of suitable soil rather than indicate a lengthy period of colonisation.[567]

Newfoundland, the glacial analogue of the British Isles on the opposite side of the Atlantic, had an independent ice-centre[568] which was weak on the east but as elsewhere, to judge from the height of the lateglacial isobases (see p. 1320), expanded beyond the present coast.[569] Labradorean ice overrode it at maximum except in the south part of the Long Range which was a nunatak and plant asylum[570] (see p. 1392).

Canada's northern strip, then as now too arid for snows to accumulate, was only feebly glaciated: its thin ice eroded little and left part of the Arctic Archipelago ice-free. The Laurentide ice, whose western edge gradually diverged from the Rocky Mountains and became lower to the north,[571] flowed over the

mainland between Mackenzie River and Coronation Gulf[572] and united on the west with valley glaciers from the Brooks Range (see below)—erratics on Mount Clark (64° 30′ N.) prove a thickness of the ice in this part of the Mackenzie basin of 1300 m.[573] Baffin Land,[574] Ellesmere Land,[575] Melville Peninsula and Southampton Island[576] had only local ice which may have been confluent. Prince Patrick Island, East Sverdrup Island and Grant Island were likewise glaciated, though it has been contended that the deep channels among the islands off north Canada are characteristic of glaciated coasts and imply that thick ice once covered much of the area,[577] including Victoria Island, King William Island, the greater part of Prince of Wales Island, but not Melville Island nor the islands to the north which have V-shaped valleys and are without lakes. There is no evidence of an extensive glaciation of the shelf of Beaumont Sea (Carsola, 1954).

Although the ice flowed northwards in northernmost Labrador,[578] it has been thought improbable that the Greenland ice united with that of Ellesmere Land[579] or Baffin Land.[580] Unglaciated terrain and numerous nunataks in west Greenland render a confluence with the Greenland ice unlikely,[581] except in the north (see p. 726) where the ice-masses coalesced over the narrow straits. The Greenland ice may have advanced 123 km or 60 miles beyond its coast.[582]

The Alaskan ice-cap,[583] in places up to 5000 ft (*c.* 1500 m) thick, was in general merely an inflation of the present valley and piedmont glaciers which floated as shelf-ice possibly to Middleton Island out in the Gulf of Alaska. There was a notable expanse of ice in the intermontane areas on both sides of the Wrangel and Alaska Ranges, and a separate centre on the massive Brooks Range, north Alaska, which was glaciated from end to end (600 miles: 960 km) and sent valley glaciers that fanned out on to the plains skirting the Bering Sea and Arctic Ocean but not to the coast itself. South of this, glaciers invaded the sea along Alaska's entire Pacific littoral: a submarine moraine, for example, crosses the outer part of Yakutat Bay and till-like marine deposits occur in the Gulf of Alaska.[584] Seward Peninsula had an independent system and the Alaska Peninsula had valley glaciers which flowed off Kenai Peninsula and covered Kadiak Island.[585] Many of the Aleutian islands were apparently heavily glaciated[586]—the snowline was at 240–300 m. Yet parts of Alaska had no more ice than to-day.[587] Thus the islands in the Bering Sea had no ice,[588] and glaciers were wanting in inner Alaska and in the main valley of the Yukon River whose low relief and dry climate were inimical: weathered forms remain undisturbed north of a well-defined line in north Alaska, and Alaska-Yukon has the following fossil fauna[589]: *Mammuthus primigenius*, *M. primigenius compressus*, *Mammut americanus*, *Rangifer*, sp., *Bison crassicornis*, *B. alleni*, *Symbos tyrelli*, *Boötherium sargenti*, *Ovibus yukonensis*, *O. moschatus*, *Oreamnos* sp., *Equus alaskae*, *E. lambei*, *Camelops* sp., *Arctodus yukonensis*, *Aenocyon dirus alaskensis* and *Felis atrox alaskensis*.

Radiation Centres. North America differed from Europe not only in the more southerly position of its iceshed but apparently in the plurality of its centres. J. D. Dana[590] argued in 1871 for such multiple centres in the North American ice. Whitney,[591] from still earlier studies in the 60s of that century, discovered them in the Coast Ranges of the west, and G. M. Dawson[592] in 1886 recognised them as situated east and west respectively of

Hudson Bay. Except that in the Cordilleras of the west, they were connected not with relief but with precipitation: they probably shifted inwards as deglaciation progressed.[593]

The Labradorean centre[594] lay east of James Bay in 50° to 55° N.[595] (since its lateglacial focus of uplift was in Quebec, "Quebec centre" might seem a preferable term[596]). The Keewatin centre (Cree Indian, *Ki-we-tin*, north or north wind) of J. B. Tyrrell,[597] the more northerly of the three, was situated in about 62° N. on a wide plain at 120–240 m east of Great Slave Lake. The Patrician centre, which Tyrrell[598] subsequently added, lay on the height of land between Hudson Bay and Lake Superior at an altitude of *c.* 290 m in 53° N. and 89° W.; its ice radiated westwards over Minnesota and southwards over Michigan and Ohio.

These three centres, forming collectively the "Laurentide Glacier" or "Laurentide ice-sheet"[599], or simply the "Laurentide Ice",[600] had on their west the "Cordilleran Glacier"[601] or the "Cordilleran ice-sheet"[602] which, notwithstanding the high relief and relative nearness to the Pacific Ocean and its overall length of 2350 miles (*c.* 3760 km) and area of 875,000 sq. miles (*c.* 2,267,000 sq. km), was inferior to the ice on the eastern plains—G. M. Dawson[603] early noticed that the ice-flow on the plains was not from the west but from the Canadian Shield. The Cordilleran ice in its growth, like the modern ice-sheets of Greenland and Antarctica (see p. 671), probably passed successively through an alpine, a mountain ice-sheet and a continental ice-sheet phase.[604] At maximum it moved outwards more or less regardless of the topography, though whether its serrated peaks were overridden or persisted as nunataks is disputed.[605] Still not well known but apparently not an ice-sheet but composed of confluent valley, piedmont and intermontane glaciers,[606] e.g. in the corridor, 1000 miles (*c.* 1600 km) long and 300 miles (*c.* 480 km) broad, between the Coast Ranges and the Rocky Mountains, it had its centre between the 55th and 59th parallels of latitude where it reached 2100 m above the mean level of the interior plateau. It may have covered the northern Rocky Mountains[607] and between the parallels of 49° and 63° N. have resembled modern Greenland. It overflowed the Coast Range through the Fraser, Skeena and Stikine Passes; filled the valleys of the Columbia, Fraser and other westerly flowing rivers; occupied the Strait of Georgia between Vancouver Island and the mainland to a depth of *c.* 900 m; impinged upon Queen Charlotte Islands; built up thick piedmont ice, as in Puget Sound and the Strait of Georgia, which streamed for several miles out upon the continental shelf; and, as in the case of the Puget Glacier in Wisconsin time, pushed up into the Cascade Mountain valleys impounding glacier-lakes.[608] Its valley glaciers overflowed the eastern passes, e.g. the Athabasca Pass and Bow Pass, in the Selkirk and Rocky Mountains, and via the Peace and Liard valleys and over a front 400 miles (*c.* 640 km) broad splayed as piedmonts upon the plains of Alberta[609] to a distance of 50 miles (80 km). Vancouver Island had its own small radiation and Queen Charlotte Islands many local glaciers.[610]

Relations between centres. The Keewatin and Labradorean sheets jostled each other over long distances; in the Rainy Lake region of west Ontario, for instance, erratics from the south-west, e.g. Winnipeg Limestones, mingle with Archaean boulders from the north-east. The amount of overlap and the exact relation of the drift sheets, as in Illinois, are not yet completely worked out though, contrary to Dawson's opinion (see p. 670), the Keewatin

ice appears to have succeeded the Labradorean centre,[611] possibly not independently but as a closing phase of ice-radiation[612] which may not have existed in pre-Wisconsin times. W. Upham,[613] agreeing with those who regard the Keewatin ice as merely an eccentric development of the Cordilleran ice (see p. 670), deemed the Keewatin and Cordilleran sheets to have been continuous. Others, admitting that the drifts of the two sheets cover the whole area, as in Alberta,[614] contend that they retained their own movements and had their peaks at different times (in Alberta, the Keewatin drift overlies the Cordilleran drift[615]) or were parted by a fairly wide corridor or lane which was partially flooded by their glacier-lakes[616] in which big erratics were rafted out. The red drift of the Patrician ice in south Manitoba and parts of Ontario, which shows no sign of erosion or weathering at its surface, is overlapped by grey drift of the Keewatin ice. Both drifts are referable to the Wisconsin glaciation[617] though a glacial terminal moraine in Alberta has been tentatively correlated with the Iowan.[618] It now seems probable that the ice-masses were confluent along a line which shifted from time to time but was never far east of the Rocky Mountains, the line running generally along the Mackenzie and Liard rivers and near Fort Nelson and Calgary to the international boundary.

Although the Appalachians may have had an independent "Appalachian System of Glaciers"[619], it is generally held, as for the Adirondacks,[620] that northern ice overrode them; striae score the summits of the Catskill Mountains at 4205 ft[621] (1282 m) and foreign erratics rest on the top of Mount Abraham and Mount Katahdin even above 5000 ft[622] (1500 m). A local glaciation after (or preceeding?[623]) the general glaciation has been demonstrated for Mount Katahdin,[624] the White Mountains,[625] and Catskill Mountains[626] and suggested for Nova Scotia,[627] the Shickshock Mountains, Gaspé Peninsula, Longe Range (Newfoundland) and the coastal mountains of Labrador.

(*b*) *Southern Centres*

Many ranges or plateaux, embracing at least 75 separate areas and a total of *c.* 35,000 sq. m (*c.* 90,000 sq. km) south of the North American *mer de glace*, nourished local glaciers[628]; their distribution closely parallels that of the relatively few and small glaciers of to-day and was especially marked where the precipitation was heaviest and in the form of snow and where the summers were short and cool. The Cascade Range of California and Oregon and the mountains of Washington had a network of valley glaciers which expanded into piedmont glaciers in the north. The Sierra Nevada[629] possessed reticular glaciers up to 60 miles (*c.* 97 km) long, and glaciers and snowfields on a considerable scale studded the Rocky Mountains as far south as Sante Fé in 35° 45′ N.; they especially characterised north-west Montana, the border of Montana and Idaho, Columbia and the Yellowstone Park. Equally important were those in the Wasatch and Uinta Mountains of Utah, in the Bighorn Mountains of Wyoming, and in the high ridges of Colorado.[630] North America's most southerly glaciers nestled in the San Gabriel and San Bernardino mountains of south California, in 34° 14′ N.[631] and in Cerro Blanco in 34° 8′ N.[632]

A glacier, up to 106 m thick and covering 26 sq. miles (*c.* 67 sq. km), capped Mauna Kea (4175 m) in Hawaii[633] (20° N.).

6. Tropics and Southern Hemisphere

(a) *Tropics*

The significance of the Pleistocene glaciation was first realised in the temperate latitudes of the northern hemisphere. Glacial investigations, apart from an occasional observation in South America,[634] only spread into the tropics and southern hemisphere much later—Agassiz[635] averred in 1872 that the tropics had passed through a glaciation and W. Sievers[636] first demonstrated it in 10° N. Lat. in central America.

Africa, the least glaciated of the continents, had glaciers on its highest peaks which rise almost from the equator.[637] J. W. Gregory[638] proved this for the first time in 1893 for Mount Kenya (0° 12′ S.; alt. 5195 m) whence glaciers descended to a level variously stated[639] as 4700 m or 3000 m. On Kilimanjaro[640] (3° 05′ S.; alt. 6015 m) they covered 350 sq. miles (*c.* 900 sq. km) and descended to 3550 m, 3700 m or 1480 m, the snouts being depressed by 900–1000 m or roughly the amount observed on Mount Kenya.[641] Those of Ruwenzori[642] (0° 24′ N.; alt. 5125 m) flowed downwards to about 1980 m. Mount Elgon[643] (1° 9′ N.; alt. 4315 m) which, unlike the above-mentioned peaks, is now destitute of ice, had glaciers which covered *c.* 75 sq. km and descended to *c.* 3300 m. Mount Sabino[644] (1° 25′ S.; alt. 4529 m) has moraines and fluvioglacial deposits at its foot. Mount Aberdare (12,845 ft: 3914 m) had its glacier as had Sattima (3900 m) in Kenya, and Mount Chillalo (13,536 ft: 4127 m), south-east of Addis Ababa, and Mount Kaka on the Somaliland plateau.[645]

Traces of a former glaciation have been discovered on Ixtaccihuatl[646] (19° 10′ N.; alt. 5286 m) and Popocatepetl[647] (19° 9′ N.; alt. 5346 m) (cf. p. 602) and on Arequipa and other mountains of central America,[648] and on Mount Kinabulu[649] in Borneo (6° N.; alt. 4230 m) and in New Guinea[650] (5° S. Lat.) where the glaciers were up to 15 km longer than the present ones and descended to about 2000 m.

(b) *Southern Continents*

From the disposition of the accessible lands in the southern hemisphere, signs of glaciation may be expected in few areas. For example, no part of Africa or Australasia except Stewart Island which was heavily glaciated[651] (or had only small cirque glaciers[652]) and none of South America except its southern tip came within the glacial latitudes in the northern hemisphere. It is, therefore, not surprising to find that South Africa had no glaciers[653] and that, except for a slight glaciation in Tasmania and the Australian Alps, the Pleistocene ice merely extended the present glaciers in New Zealand and the Andes. This range, whose great altitude and extension through almost 70° of latitude make it unrivalled for the study of Pleistocene glaciers in lower latitudes, had a glaciation[654] which, broadly speaking, became more intense as the latitude increased; glaciers protruded far from the mountains only in Patagonia and Tierra del Fuego (fig. 135).

Glaciers ranged from Cape Horn (56° S.) to Sierra Nevada de Santa Marta (11° N.) except for a possible gap between 4° S. and 6° 30′ S. They occurred, for instance, in the Andes of Peru,[655] Bolivia,[656] Chile,[657] Columbia[658] and Ecuador[659] where they were of the plateau type and descended on an average to 4000 m, i.e. 600–800 m below the present limits.

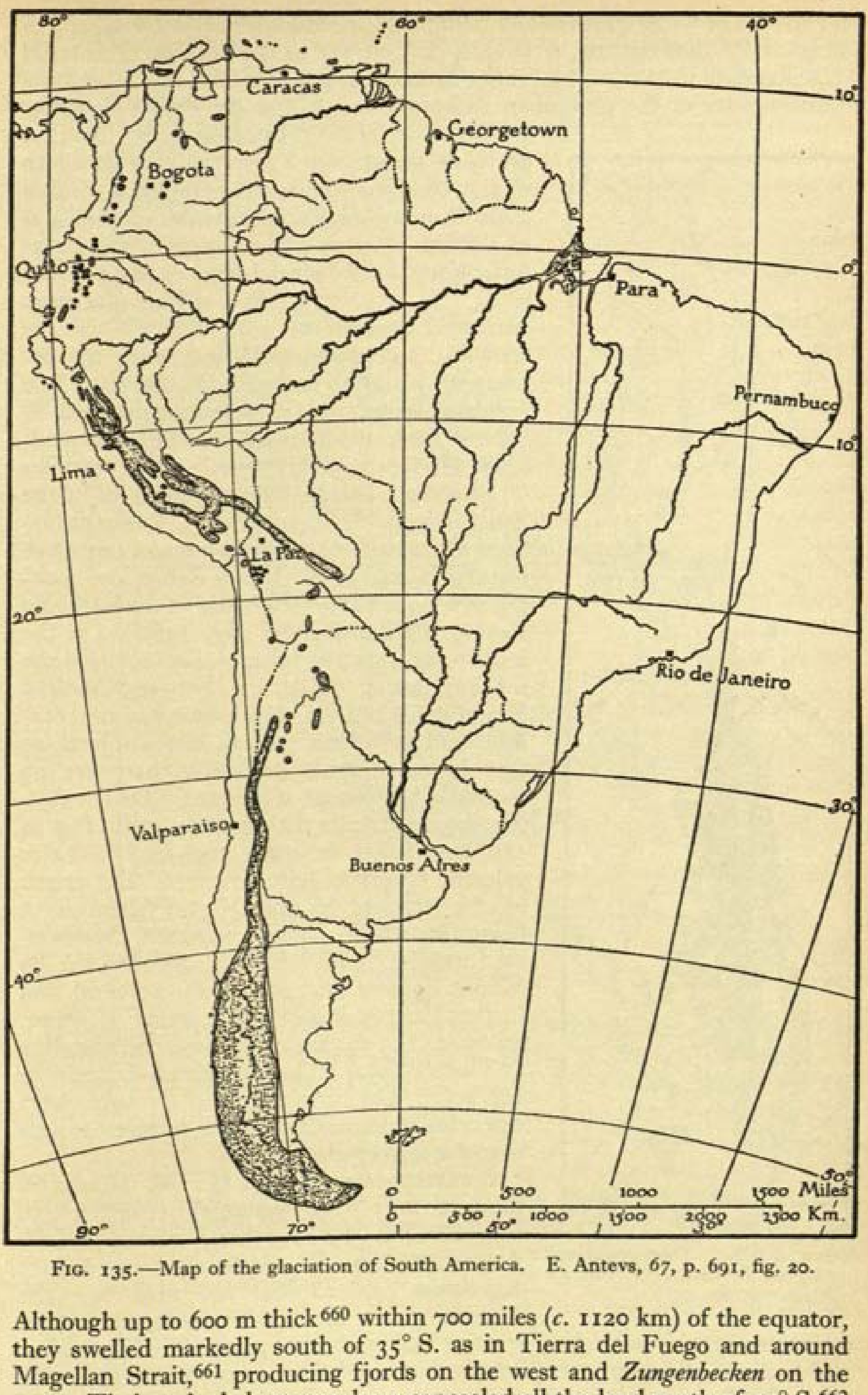


FIG. 135.—Map of the glaciation of South America. E. Antevs, 67, p. 691, fig. 20.

Although up to 600 m thick[660] within 700 miles (*c.* 1120 km) of the equator, they swelled markedly south of 35° S. as in Tierra del Fuego and around Magellan Strait,[661] producing fjords on the west and *Zungenbecken* on the east. Their united sheet may have concealed all the land south of 52° S.[662]

and an area of three-quarters of a million square miles (*c.* 2 million sq. km) in Patagonia[663] though this, it is said, is contrary to the survival of the old Magellan flora in sheltered localities in the west of the mountains[664] and the unfrozen state of the ground in Patagonia and Tierra del Fuego as earthworms prove by their distribution.[665] Erratics are widespread over Patagonia, notably south of the Gallegos River: the Patagonian Pebble Beds[666] are either glacial outwash or products of shifting rivers in a dry climate. The equatorial limit of tidal glaciers was displaced from *c.* 45° S. to *c.* 37·5° S.[667] The glaciation narrowed northwards with the rise of the snowline and south-westwards with the decreasing elevation of the mountains. The Falkland Islands (660 m) were not glaciated.[668]

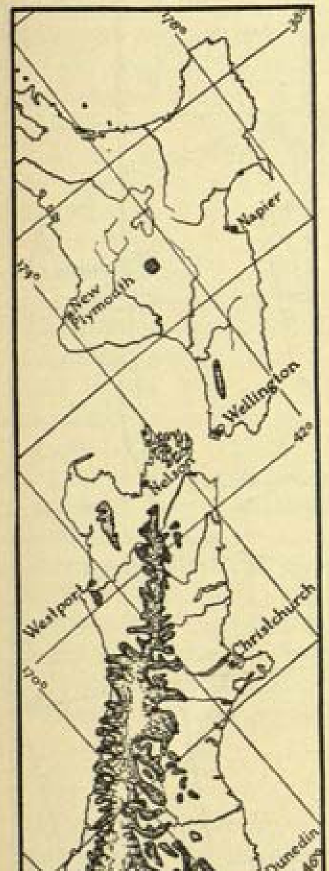


Fig. 136.—Map of the glaciation of New Zealand. E. Antevs, 67, p. 695, fig. 21.

New Zealand's network of valley and piedmont glaciers occupied over 10,000 sq. miles (*c.* 25,000 sq. km) or roughly one-third of the South Island[669]; for north of 43° S. the glaciation was small—the northernmost centre of dispersion was in the Hardy Range and rock-glaciers alone have been found in the Kaikoura Range, Marlborough[670] (fig. 136). On the south-west, south of Ross, glaciers invaded the sea but farther north, e.g. between Milford Sound and Hohitika, they terminated near sea-level and still farther north halted inland, so that in the Nelson Peninsula there are no moraines below 2000 ft (600 m). On the east, the glaciers, despite their great lengths of up to 180 km, failed to reach the sea.[671] Later volcanic eruptions have prevented the extent of the glaciers in the North Island from being known.[672] They occurred, however, on Ruapehu[673] (39° 20′ S.; alt. 2803 m), on Mount Egmont (39° 20′ S.; alt. 2520 m) and in the Tararua Range[674] (1540 m); *c.* 57 sq. miles (*c.* 144 sq. km) lay above the snowline (Willette, 1950). The Auckland Islands in 50° 40′ S. Lat. south of New Zealand, have extensive moraines and other features indicative of a former glaciation.[675]

Contemporary glaciers (F. W. Hutton[676] thought they were younger), covering 150 sq. miles (*c.* 390 sq. km), existed in the Australian Alps,[677] especially on Mount Kosciusko (36° 28′ S.; alt. 2198 m), the highest point in the continent, as roches moutonnées, cirques, lakes, erratics and moraines prove—the final stage was a cirque glaciation. In Victoria the only definite traces of this glaciation are at Big Bogong Mountain (1984 m). Plateau and valley glaciers, up to

2000 ft (600 m) thick at the maximum, buried roughly one-third or one-half of Tasmania,[678] including the Central Plateau, and protruded in places into the sea: valley and cirque-glaciers represent the later stages[679] (fig. 137).

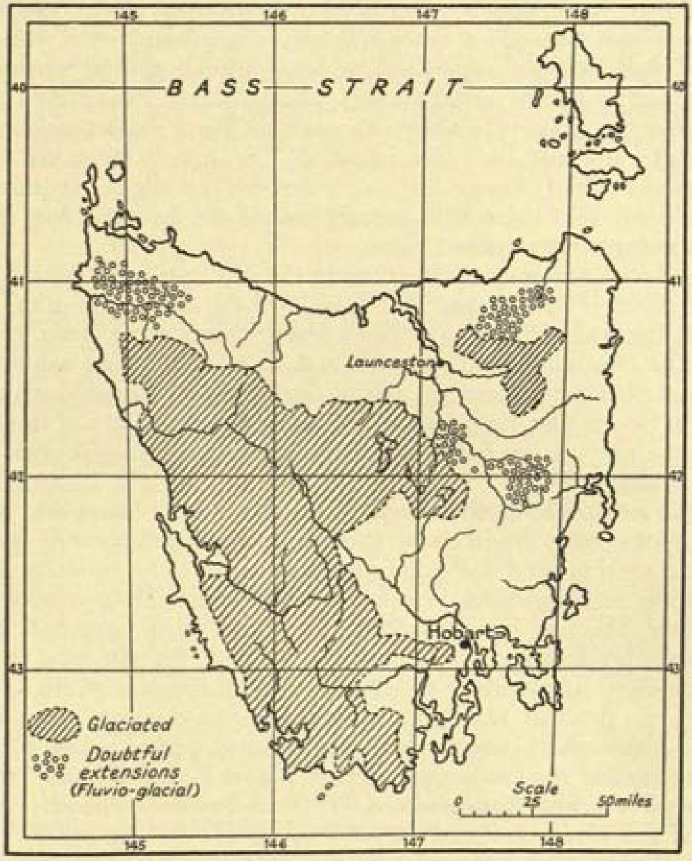


FIG. 137.—Map of Tasmania showing the extent of the glaciations. A. N. Lewis, *P. R. S. Tasm.* 1944, p. 43.

Macquarie Island, about midway between Tasmania and New Zealand, was overridden by ice from an area to the west now down-faulted into the sea[680]: erratics were uplifted 1200 ft (*c.* 360 m) from outcrops on the west coast.

(*c*) *Antarctica*

The subantarctic islands, except apparently Bouvet and the Balleny Islands,[681] had a much severer glaciation. This applied, for example, to Heard Island[682] and to Kerguelen[683] and South Georgia[684] which were almost wholly ice-covered.

Striae and roches moutonnées, erratics and moraines demonstrate decisively that the Antarctic ice at one time spread far above and beyond its present boundary. This important fact, first proved by R. F. Scott,[685] has been confirmed by all later observers, as in Graham Land[686] (the ice was at least

300 m higher), in Kaiser Wilhelm Land,[687] where the ice was 350–400 m thicker and gneissic erratics were conveyed to the summit of the volcanic Gaussberg (371 m), and in the Edsell Ford Range[688] (the ice was *c.* 600 m thicker). In South Victoria Land,[689] the Beardmore Glacier was 600–1200 m higher, Robertson Bay was filled to more than 300 m, and the small valleys to at least 600–900 m: moraines near Cape Adare are *c.* 300 m above sea-level. Ross Barrier, supported on long skeletal ribs or aground, projected far out from the outlet glaciers, abutted upon Ross Island to 240 or 335 m above the present limit[690]—the present Ross Barrier only came into existence after the land-borne ice retreated. Erratics likewise prove that the ice of Mount Fridtjof Nansen was much deeper,[691] while the rounded mountain sides prove that the whole country east of the Liv and Axel Hamburg glaciers was formerly glaciated.[692]

In accord with previous observations in the Alps (see pp. 644, 715), Greenland (see p. 725), Spitsbergen and Alaska,[693] the added elevation over the interior of the Antarctic ice was much less[694]; near the plateau it was only 60 m, in the Dronning Maud Land *c.* 240 m or more, along the sides of the nunataks of Neu-Schwabenland 400 m (including its *Stumpflinge*) and near the coast of South Victoria Land 600 m. The fact that many of the Antarctic cirques are empty or are bounded by abandoned moraines proves a former greater glaciation.[695]

That the ice spread farther north is suggested by erratics and striae and possibly by the relict origin of the shelf-ice (see p. 171), the low level of the continental shelf around the Antarctic (see p. 1346), the morainic shoals and immense terminal moraines, a few hundred metres high, outside the ice-sheet,[696] e.g. Mawson Bank off Adélie Land and King George V Land and Davis Bank off Gaussberg and Queen Mary Land, the nature of the detritus on the sea-floor surrounding the continent[697] through a width of 200–700 miles (*c.* 320–1100 km), and by the diatom ooze found beneath the globigerina ooze.[698] Although its outermost limit at the peak period is unknown, the ice probably travelled 100 km farther north in Kaiser Wilhelm Land[699] and filled the sounds in the Ross Sea quadrant.[700] Ross Barrier, resting heavily on the bottom of the sea, was thrust forward up to 200 or 300 miles[701] (*c.* 320–480 km). Submerged moraines form the Pennell and Iselin banks[702] and lie off Kemp Land[703] while Proclamation Island (1485 m), east of Enderby Land, is completely glaciated and has erratics on its summit.[704] Ice filled Gerlache Strait off Graham Land to a depth of 800 m,[705] transporting erratics to this land and submerging it to the outer islands.[706]

The ice may have reached 63° S. Lat[707] or may have been bounded by the edge of the continental shelf[708] as in Europe (see p. 714). The suggestions that the ice of New Zealand and South Victoria Land was connected[709] or that the Antarctic ice invaded the coastlands of south Australia[710] or extended to other continents[711] are entirely without foundation[712]: the wide open Southern Ocean militated against a great expanse. Its mass, during the last glaciation, may have been greater by one-third or approximately 4 million cu. km.[713]

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J.* 34, 1909, 483. **690** *356*, 790. **691** *631*, 863. **692** *629*, 202. **693** *1439*, 183. **694** *840*, 413; *1910*, 131, 136; L. M. Gould, *Sm. I. Rp.* 1932, 244. **695** *1886*, 737; *1910*, 153. **696** *56* (8); D. Mawson,

G. R. 20, 1930, 547; *Rp. Austr. A.* 22, 1935, 30. **697** *1313*, 586; J. L. Hough, *J. G.* 58, 1950, 254. **698** *55*, II, 457. **699** *432*, 43. **700** *1840*, 437, 439. **701** *356*, 790; *629*, 234; *1545*, II, 276. **702** *1688*, 160; D. Mawson, *op. cit.* 30; S. E. Roos, *G. R.* 27, 1937, 577. **703** D. Mawson, *op. cit.* 547. **704** *Ibid.* **705** J. G. Andersson, *op. cit.* **706** *799*, 118. **707** *1122*, 668. **708** *1840*, 222. **709** *1246*, 267; J. Park, *G. Sv. N. Z. B.* n.s. 7, 1909, 43. **710** F. P. Shepard, *P. Nat. Ac. Sc.* 22, 1936, 501. **711** J. Park, *op. cit.* **712** *1633*, VII (1), 30; G. M. Thompson, *T. N. Z. I.* 42, 1909, 348. **713** *338* (2), 46.

Chapter XXXIII

GLACIATION OF THE BRITISH ISLES

General. The British Isles, by virtue of their configuration and westerly position, formed a "mountain ice-sheet", an independent though composite centre of radiation on the periphery of the Fennoscandian ice. The dominant mountain-clusters served as ice-radiants. They were mainly in the west which was most elevated and received the most copious precipitation as it does to-day. The wide diversity of the rocks and the varied compositions of the drifts and erratics, supplemented by the abundance of striae and kindred rock-scorings, especially in the mountains, make it easy to deduce the currents of ice (fig. 138).

Influence of Fennoscandian Ice. The Fennoscandian ice was near the east coast. It deposited true Scandinavian drift in Aberdeenshire,[1] including the "indigo boulder-clay"[2] at Ellon with fragments of marine shells (*Cyprina islandica*, *Astarte arctica*) carried up by local ice pressed in upon the land. To it also belong the sands and gravels with rhomb porphyry and laurvikite at the Bay of Rigg[3] (14 boulders) and laurvikite and other Scandinavian erratics of coastal Aberdeenshire, Moray Firth[4] and the Orkney Islands[5] which were either derived from these beds or drifted by floating ice. It likewise deposited Scandinavian drift at Warren House Gill on the Durham coast[6] (exclusively south Norwegian erratics and now almost covered by a colliery tip-heap) lacustrine leaf clays containing flint and chalk in the Tyne valley[7] and Scandinavian erratics in the English drifts[8] as far west as the Cotswolds (fig. 129, p. 713). Mentioned first by J. A. De Luc[9] and later by L. v. Buch[10] and thought to have been brought over as anchor-blocks or ballast,[11] they embrace rhomb porphyry, laurvikite, nordmarkite, sparagmite, elaeolite syenite Christiana pink soda-granite, Särna and Elfdal porphyries, saussurite gabbro from west Norway, garnetiferous mica-schist, Rapakivi and Ångermanland (?) granites from the Baltic, Scanian basalts (?), cancrinite syenite from Särna, sparagmite conglomerate from Scania, pyroxenite from Fettnedt (Oslofjord), labradorite porphyrite from Mos (Skagerrak), halläflinta from east Småland, and red flints from Denmark. The transport may have been direct[12] or more probably indirect[13]—the percentage of the erratics is small, they are associated with Scottish erratics in the Yorkshire drifts, and they become more numerous southwards, e.g. through Yorkshire and Lincolnshire.

The Fennoscandian ice charged the Basement Clay (see p. 763) with sands enclosing arctic marine mollusca. It thickened the British ice and compelled this to find its principal relief on the west, thereby occasioning congestion in the Irish Sea and reversing the flow in the Solway Firth and Vale of Eden.[14] It disputed the sway of the British glaciers along the whole eastern coast from the far-off Shetland Isles and less remote Orkney Islands in the north to Norfolk in the south. From a dividing line about the Firth of Forth, the ice was bent to the north-east out of the Forth and Tay, northwards over Aberdeen and Caithness, and north-westwards over the Orkney Islands, and made

to flow south-eastwards over the eastern Lammermuir Hills and the Berwickshire coast. The Tweed ice curved round the eastern shoulders of the Cheviot Hills, as proved by striae and drumlins, e.g. in Berwickshire and Roxburgh, and the Tyne and Tees ice was similarly deflected. While, however, in Scotland and northern England the local ice, though modified severely in its

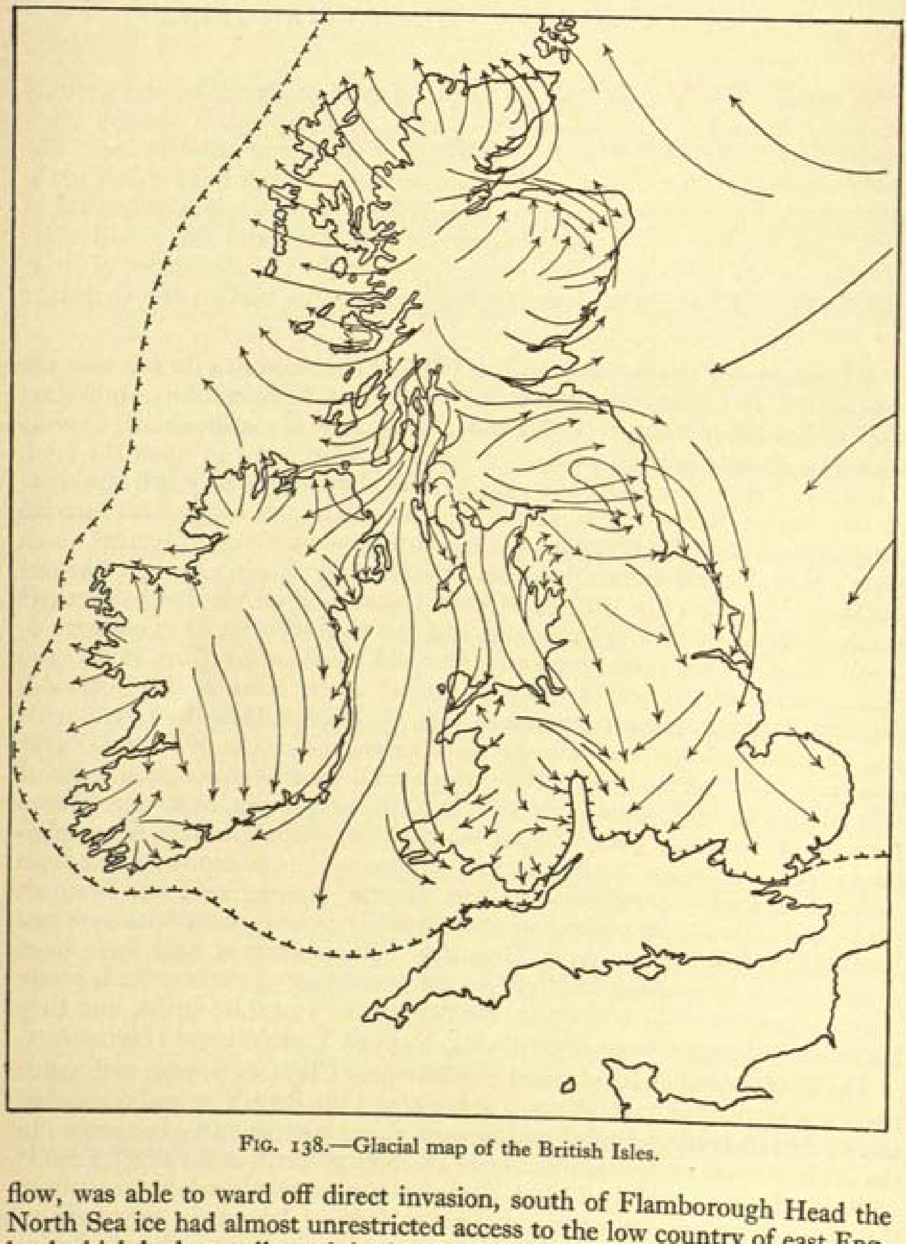

FIG. 138.—Glacial map of the British Isles.

flow, was able to ward off direct invasion, south of Flamborough Head the North Sea ice had almost unrestricted access to the low country of east England which had a small precipitation and was far from the controlling centres of dispersal in the west.

Before this pressure was exercised, the local ice spread beyond the coasts.

It engraved striae tending north-eastwards in Northumberland[15] and deposited local boulder-clay near Wick[16] and Aberdeen[17] (with moraines) and moraines, with boulders of Shap granite, at the "Rough Ground" about 20–40 miles (32–64 km) seaward from the mouth of the Tees.[18]

1. *Scotland*

Highlands. The Scottish Highlands, like the rest of glacial Britain, were buried under a vast sheet of confluent glaciers—An Teallach (3483 ft: 1061·5 m) and Ladhar Bheinn (3343 ft: 1019 m) in the west may have been nunataks. Their radiants were about the highest elevations, as north and south of Loch Maree and in Assynt and other parts of Sutherland.[19] The lines of flow were guided near the base by the grander topographical features but in the upper layers departed strongly from the valley trends and at one period issued from an eccentric parting east of the main watershed in the north-west (see p. 668). On the east, the ice encountered that from Fennoscandia (see above) and on the west overflowed the lower islands and even Jura but encircled the local ice-caps of Arran, Mull and Skye.

Ice from the Monar centre flowed roughly eastwards to Cromarty and Dornoch firths, carrying with it erratics of Moine gneiss, quartz granulite and the readily recognisable Inchbae augen gneiss. The latter, situated astride the iceshed, sent erratics westwards, e.g. to Loch Broom, and eastwards over all the country east of its outcrop, even on to the highest divides, save the top of Ben Wyvis which had a small ice-cap.[20] They streamed across Black Isle to Cromarty and Moray firths and over Beauly and Dornoch firths to the plain of Moray and Banff and were scattered far and wide over the seaboard of Easter Ross. Their southern limit passes from Loch Luichart to Beauly Firth and crosses the River Orrin just above its junction with the Conon.

Examples of westerly transport are the gneiss and schist found at great heights on the Torridonian rocks, e.g. over the entire Applecross Peninsula, and thrust-Torridonian sandstones from near Loch Carron which were conveyed to the summit of the Cambrian quartzite of Meall a' Chinn Dearg[21] (3095 ft: 943·5 m) and the plain west of the Moine thrust. Boulders of Cambrian quartzite and Torridonian sandstone bestrew the whole Lewisian area of the west. This westerly or north-westerly carry agrees with the boulder-trains from the various members of the Lewisian itself, e.g. serpentines and peridotites, and with the Lewisian boulders which rest on Torridonian sandstone west of Gruinard Bay.

Rannoch Muir was another great gathering ground; its radiating glaciers carried erratics of the Rannoch Muir granite, e.g. into Glen Lyon, Strath Tummel, Strath Tay and Glen Almond. This dominant movement in the east is confirmed, for example, by striae on Schiehallion at 3000 ft (*c.* 915 m) trending S. 20–60° E. and by the carry of Ben Vuroch granite boulders to Kirriemuir, Angus.

Ice from the Cairngorm Mountains, the biggest area of continuous high ground in Britain, threaded its way eastwards down the Dee. From Gaick Forest and Beinn Dearg it streamed southwards into Perthshire and northwards to the tributaries of the Spey: it arrested the easterly flow from Rannoch Muir.

Ice from the west overrode the almost featureless Monadhliath Mountains, whose summits approximate to 3000 ft (*c.* 900 m). That from the Great

Glen crossed obliquely the valleys of the Nairn, Findhorn and Spey—erratics of Old Red Sandstone from the Ness basin occur on the south side of the Strathnairn Hills and as far east as Loch Moy and Tomatin on the Findhorn and the watershed with the Nairn. Erratics of the granites of Kinsheary and Ardclach travelled to Banff and Elgin respectively and those of the Moy granite to between Dallas and the River Spey.

The big depression of Loch Linnhe largely determined the course of the ice which, fed by converging currents from either side, flowed south-westwards. The Linnhe ice was joined by powerful masses which swept down Loch Leven and along the flanks of the Ben Nevis range from the eccentric iceshed about Rannoch Muir (see above). The combined stream carried Ben Nevis granite to the south-west, Glencoe volcanics to Ballachulish, and kentallenite from Kentallen along Loch Linnhe. Farther west, erratics of the Morven granite were moved south-westwards to the Ardamurchan peninsula while on the south Old Red Sandstone and volcanic rocks of the mainland were conveyed over Jura and Scarba and possibly to Colonsay.[22]

In the south-west Highlands, the movement was generally south-westwards; it was controlled by the major glens of Etive and Orchy through which the ice wound from Rannoch Muir. From this source the whole country east of Loch Awe was at one time overridden since rock-types from Glen Orchy bestrew the highest parts. Between Loch Awe and Oban, the flow was generally slightly south of west. Granite boulders about Loch Awe are invariably of the Ben Cruachan type, the Glen Etive type being confined to the path of the Glen Etive ice.

Loch Fyne similarly dominated the flow in Mid-Argyle though there was divergence to the south-south-east along Loch Goil, Loch Eck and Loch Striven to the Firth of Clyde and westwards along the Crinan depression to the Sound of Jura. Erratics of the Garabal Hill granite are distributed along Loch Eck, Loch Long, Gareloch, Loch Lomond and the Firth of Clyde.[23]

Skye[24] had a local centre in the Cuillin Hills and Red Hills. At an early stage, its ice probably extended on to the lower parts of the mainland since erratics from Skye (Mesozoic and Durness limestones) are found in the extraneous drift. At the climax, it withstood the mainland-ice on the line Broadford–Loch Eishort–Kyle of Scalpa and the Narrows of Raasay. Within this area of *c.* 400 sq. miles (*c.* 1000 sq. km) Highland erratics are absent and striae are disposed radially. As the distance from the centre increased, the Skye ice conformed more and more to the extraneous flow which curved round it on the east and south, distributing Moine gneiss erratics at all altitudes on Scalpa and Raasay and about the Sleat of Skye.

Mull also cradled glaciers[25] which lasted throughout the Ice Age, though mainland ice invaded the margins of the island from the south-south-east and scattered its erratics profusely, e.g. Morven granite, Moine gneiss, Trias sandstone (from the bottom of the Sound) and a few quartzites. Influenced partly by the Irish Ice, it proceeded north-westwards over Iona, Tiree and Coll.

Mainland ice overrode the islands of Rhum, Canna, Eigg and Muck from the south-south-east.[26] It carried Highland erratics, e.g. mica-schist and garnetiferous gneiss, Torridonian rocks from the floor of the sea, and granite, gabbro and Durness Limestone from Rhum.

The Outer Hebrides were glaciated by ice which crossed the Minch from Skye, Ross and Sutherland, with a westerly component that lessened as the

islands are followed northwards.[27] Nunataks,[28] excessively frost-shattered, projected in South Harris, South Uist and Lewis, though in W. Panzer's opinion,[29] Lewis was completely overridden. Mainland erratics, comprising Torridonian Sandstone, Cambrian grit and limestone, Moine gneiss, and chalk flints (from the sea-floor) sprinkle the hillsides.[30] Arctic shells and foraminifera are embedded in the drifts of the plain of Lewis[31] but are lacking from the remainder of the Outer Hebrides possibly because the shell-laden ice was deflected as undercurrents north-east and south-west along the Minch and only the higher, clean ice crossed the islands.[32] The marine fauna about the time of the upper boulder-clay contained such cold forms as *Pecten* (*Chlamys*) *islandicus*, *Macoma calcarea*, *Astarte borealis*, and *Mya truncata* var. *uddevallensis*.[33] Ice overrode North Rona and the neighbouring islands from the south.[34]

Southern Uplands and Midland Valley. The ice in the Southern Uplands was dispersed from the mountains of Galloway,[35] the high ground between the Nith and Clyde,[36] and from plateau glaciers at the head waters of the Ettrick, Yarrow and Tweed.[37] It flowed down the master valleys and carried its characteristic rocks, e.g. Silurian greywackes, with it. On the north, it joined the Highland ice, the combined stream completely filling the Midland Valley and burying the Ochil Hills of Perthshire and the Lomond Hills of Fife. Moving to the south-east or south-south-east it moulded in this direction the drumlins at Clackmannan and Glasgow and between Falkirk and Linlithgow; fashioned crags and tails, e.g. Necropolis Hill, Glasgow, Castle Rock and Arthur's Seat Edinburgh, and Traprain Law in East Lothian; inscribed striae on the summit of the Lammermuir Hills[38]; distributed the local erratics, e.g. volcanic rocks of the Kilpatrick Hills, Campsie Fells, Ochil Hills and Pentland Hills, the dolerite of Corstorphine (found at Leith and Portobello), and of the Cleish and Lomond Hills, carried to the east coast, and the Craigmillar Sandstone of Edinburgh dropped at Dunbar.

Highland erratics were deposited on the tops of the Pentland Hills, e.g. on Allermuir Hill,[39] on the summits of the Ochil and Sidlaw Hills,[40] and as far away as the heads of the Esk and Lyne valleys, the eastern headland of Fife, the northern foot of the Lammermuir Hills and at Duns and other places in Berwickshire.[41] Boulders of the Garabal Hill granite (see above) were conveyed to the south shore of the Firth of Forth, e.g. to Granton and Leith, and of the Old Red Sandstone Conglomerate from the Highland border at Callander and Aberfoyle to Edinburgh.

This flow was subject to topographical and other variations. On the plains of Ayrshire, for instance, the varying strengths of the contending glaciers from the Southern Uplands and the Highlands led to a crossing of the striae, e.g. in the Kilmarnock area,[42] and to a modification of an earlier east-west set of drumlins by a later north-south set.[43] The erratics were mingled—for example, Haggis rock and radiolarian cherts from the south were transported to Glasgow, and Highland erratics crossed the Paisley and Renfrew Hills to Irvine, Kilwinning and Darvel.

The Galloway ice on the north, e.g. that moving over Loch Doon, formed a diamond-shaped flow with the Highland ice[44] (fig. 139) and was deflected through west to south-west and forced to move coastwise in south Ayrshire as striae and erratics from the Doon and Dee granite prove. Laden with countless boulders of this granite and of sedimentary and igneous rocks from

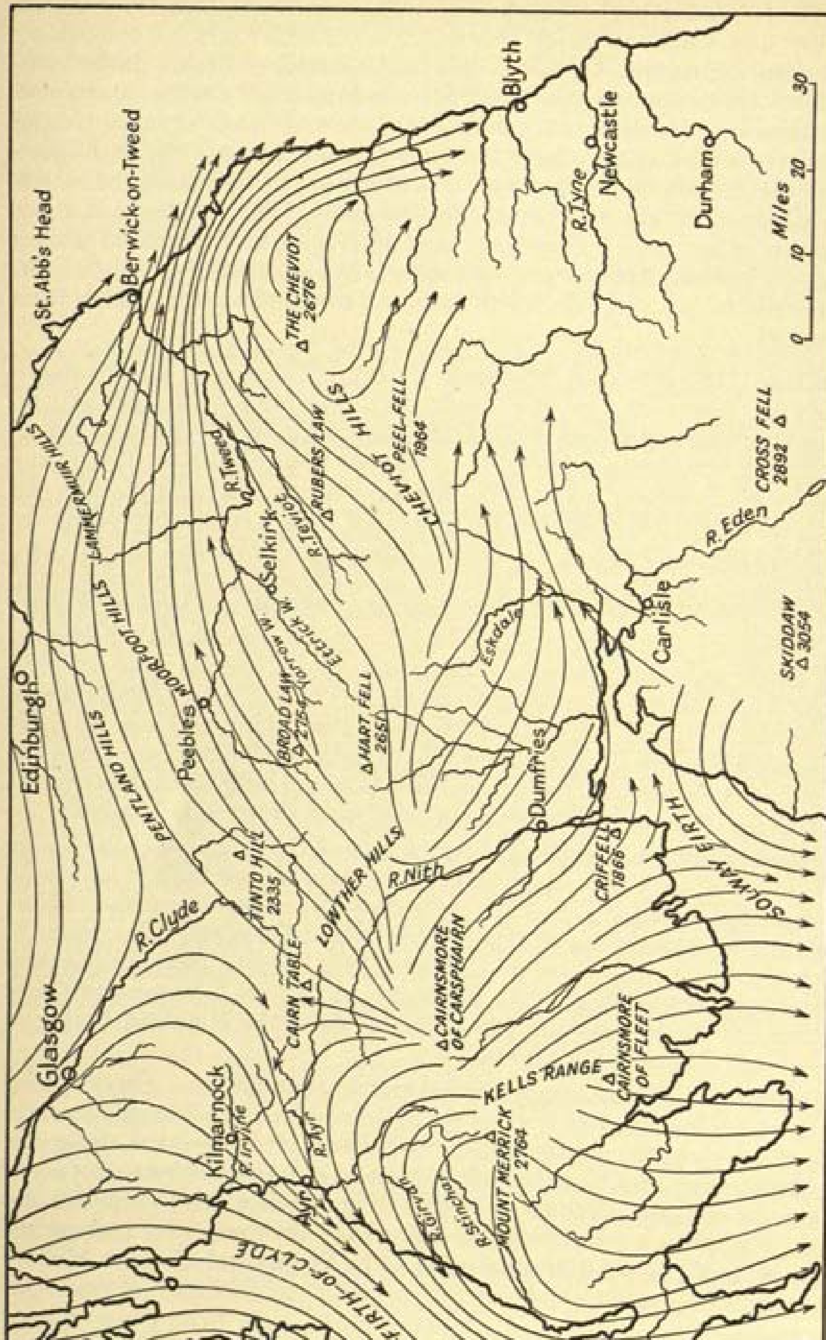

FIG. 139.—Lines of ice-flow over southern Scotland. *Mem. Geol. Surv. Scot. Reg. Geol.*, "South of Scotland", Ed. 2, 1948, p. 81, fig. 14.

Ayrshire, it passed off the coast and on to the Rhinns of Galloway, there to dump some of its material with Cretaceous flints and shelly fragments dredged from the sea-bottom (see fig. 113, p. 632).

The congestion in the Midland Valley was relieved by a fanning on the east. The ice after moving eastwards over East Lothian swung on to a south-east course parallel with the coast. It overflowed the northern spurs of the Lammermuir Hills and the broad Merse of Berwickshire and transported coal from Haddington to Oldhamstocks, Highland erratics to the Tweed, and boulders from Eskdale over the lower cols to the Teviot.

Strathmore ice advanced northwards along the coast of Angus and Aberdeenshire[45] as far as Peterhead, extending for 10 miles (*c.* 16 km) up the Ythan valley and for a few miles up the Dee where its red clay is preserved in sheltered patches east of prominences.[46] It dredged up marine shells from the sea-floor, together with Cretaceous boulders and fossils,[47] and numerous rolled and weathered flints[48] derived from the same source or from Pliocene terrestrial gravels. The material was deposited in a red clay, formed of disintegrated Old Red Standstone rocks from Kincardine and the traps of this county and Angus, which lies east of a line that falls from 90 m near Aldie to 60 m north of Stirling Hill and 30 m west of Peterhead. The Strathmore ice, in its cleaner part, poured over the Carron-Cowie divide to the Dee watershed.[49] In north-east Aberdeenshire, Moray Firth ice offered opposition and carried Inchbae gneiss erratics to between Fraserburgh and Aberdour, Cambrian pipe-rock from the North-west Highlands to Cullen in lower Banffshire and near Turriff and Maud,[50] and boulders of Mesozoic rocks, e.g. Lias and Oolites from Elgin and Speymouth across Banffshire to Peterhead and as far as Ellon. This ice laid down the black-blue boulder-clay of the Banffshire coast[51] though this is in places slightly earlier since patches of it containing granite boulders from the south are locally encased in red clay.

The eastern strip of the Caithness plain was overridden from S. 20° E.[52] (later from the south, after the Scandinavian barrier had shifted somewhat eastwards). This is shown by striae, by marine shells of boreal, arctic and southern species, and by the carry of erratics, such as Sarclet conglomerate, Inchbae augen gneiss, Cambrian pipe-rock, Mesozoic rocks and fossils (including belemnites, jet and fossil wood), chalk and flints and the Leavad erratic (see p. 363). This powerful ice deflected the local glaciers issuing from Berriedale, Dunbeath and other glens through north-east, north and finally north-west; the line of confluence, which was liable to oscillate as cross-striae and the mingled boulder-clays show, runs from Berriedale to Reay (fig. 140).

Orkney and Shetland Islands. In harmony with this movement was the glaciation of the Orkney Islands[53] by extraneous ice from the south-east and south-south-east. Flowing independently of the physical features and deviating but slightly as it impinged upon the eastern slopes,[54] it introduced marine shells and foraminifera, Mesozoic rocks (chalk, flint, oolite), Highland schist, gneiss, quartzite, epidiorite, granite and gabbro, and Carboniferous limestone (? from Fife).

The Shetland Isles were surmounted from the east, with zig-zag deviations controlled by the relief.[55] This is evinced by striae and the transport of local rocks—Mesozoic erratics and marine shells are absent, possibly because the islands then stood higher.[56]

Glacial succession. East Scotland experienced a threefold glaciation [57] to which striae, erratics and boulder-clays of different compositions testify; a few sections show all three drifts in direct superposition. The first ice fanned over Moray Firth and overflowed north Aberdeenshire from the west or north-west, carrying with it Cambrian pipe-rock, Torridonian sandstone,

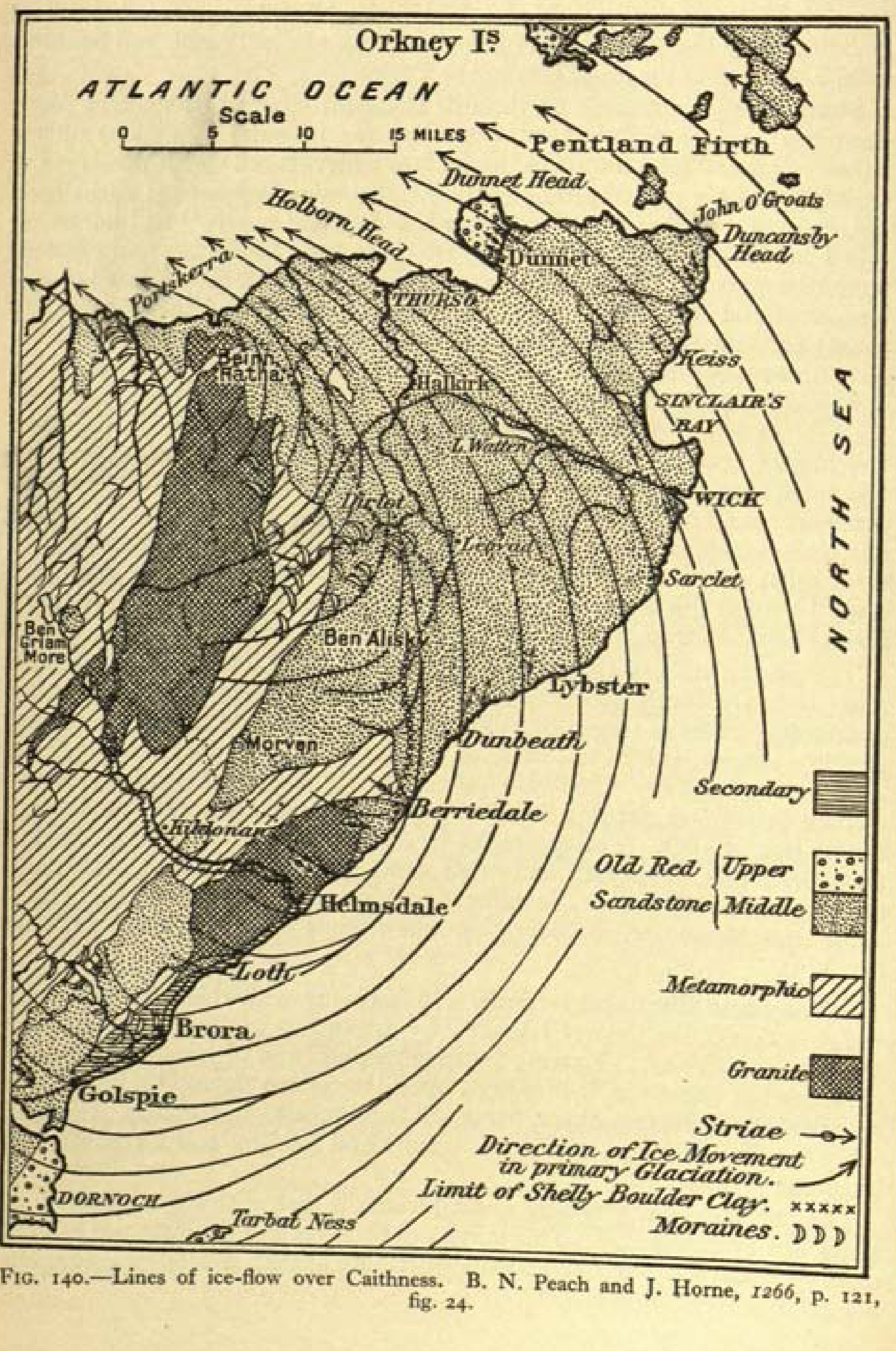

FIG. 140.—Lines of ice-flow over Caithness. B. N. Peach and J. Horne, *1266*, p. 121, fig. 24.

Elgin Sandstone and much Jurassic material (about Banff and Huntly); Sutherland granites were conveyed to Elgin. It moved southwards over Aberdeen with debris from the Huntly igneous complex and as far west as Alford, and proceeded to Montrose, Kincardine and Angus, impelled along this course by Scandinavian ice out to sea.

The second ice, which followed a deglaciation represented by the Benholm peats (see p. 1011), had centres in the Banffshire Hills south of the Moray Firth as well as farther west in the Cairngorm Mountains. Belonging apparently to Scotland's "maximum" glaciation[58] it moved uniformly northwards over eastern Scotland, e.g. over Aberdeenshire and the Moray Firth, Caithness and the Orkney Islands—chalk flints, dredged from Moray Firth, occur in its red boulder-clay in coastal Sutherland and with marine shells in Caithness and the Orkney Islands. It picked up Inchbae augen gneiss, Lewisian gneiss and Cambrian quartzite, dropped by the first ice on the bottom of the firth, and carried them northwards into Caithness. On the east it was confluent with the Strathmore ice which, charged with a copious red bottom moraine formed by grinding up the soft red shales of Strathmore and the shales, sandstones, conglomerates and lavas of the Old Red Sandstone, transported volcanic ash from the Ochil Hills into the Orkney Islands.

The third sheet fanned out over Moray Firth from the Northern Highlands and the region east and west of the Great Glen with a variable axis that was short of the coast between Fraserburgh and the Ythan and passed out to sea between here and Aberdeen (Bay of Nigg). The Banffshire Hills, Cairngorm Mountains and Central Highlands contributed their quota. Ice flowed out to the Bervie, North Esk and South Esk valleys.

Firth of Clyde. Firth of Clyde ice, supplied with Highland erratics, poured southwards over Bute and the Cumbraes and overrode all but the highest peaks of Arran which persistently nourished independent glaciers.[59] It flowed westwards over Kintyre,[60] transporting countless boulders of the Arran granite (these were nowhere carried by the ice to the Ayrshire coast[61]); crossed Knapdale from the east-north-east, taking the Loch Fyne porphyry as erratics to Jura, Islay and Colonsay; and moved south-westwards over Cowal.[62]

Islay was glaciated from the south-east[63] and Colonsay and Oronsay from the east,[64] most of the erratics being white quartzites, pebbly grits and cream-coloured dolomite from Jura, and Garabal Hill granite porphyry, and other rocks from the Loch Awe and Loch Fyne region.[65] Jura was invaded from the south-east.[66]

2. *England and Wales*

Lake District. The Lake District, as Agassiz and Buckland first recognised,[67] was severely glaciated. Subsequent investigations,[68] summarised by Marr,[69] revealed a local centre whose ice engraved radiating striae, notably on the Borrowdale igneous rocks, and transported erratics valleywards from the present watershed, i.e. from Scawfell, Dunmail Raise, High Street and Shap Fells. For example, the Buttermere granophyre, which bestrides the main iceshed, was transported as erratics[70] on the north down the Vale of Lorton and Cocker Vale to the Cumberland plain, e.g. Cockermouth, Whitehaven and St. Bees, and down Ennerdale, Wastdale and Crummock Water; Borrowdale volcanic rocks were carried outwards on to the Skiddaw

Slates and the annular ring of Carboniferous Limestone. At an early stage, the ice discharged freely in all directions and, as the anomalous distribution of certain Cumbrian erratics suggests, may have attained the sea on the west.[71] Its boulder-clay, grey with Carboniferous and Lake District material, is preserved in the Derwent valley and east of the Ellen.[72] It failed, however, to reach the north end of the Vale of Eden where Shap granite and other erratics from southern Edenside are absent—Shap granite occurs as far north as Dufton and Melmerby; a boulder-clay in the River Caldew containing very badly weathered Lake District erratics probably represents the earliest accumulation.[73]

Advancing Galloway and Irish Sea Ice, influenced by that in the Solway (as is seen in the increasingly westerly trend of the Galloway ice over Wigtownshire and in the easterly flow over Mount Criffell and the Nith about Dumfries), blocked the way to the sea across the Carlisle plain. It thickened the local ice so that this glaciated the topmost land in the Ullswater area[74] and compelled erratics (e.g. Eycott Hill lavas and Carrock Fell gabbro) from the northern Lake District to go round into the Maryport area.[75] Splitting the ice from Borrowdale, it sent a bigger stream to the Vale of Lorton and the Irish Sea and a smaller one up the Gretna valley into the Tees.[76] It also turned the Ennerdale and Eskdale glaciers southwards, uniting with the one about Bootle and with the other about Whitbeck, though each for a time preserved its identity and travelled coastwise with the Irish Sea Ice. This western ice finally invaded the Fleetwood and Blackpool coasts.

Irish Sea drift, red in colour and embracing Galloway erratics (first identified as such by A. Sedgwick[77]), e.g. Criffell granite and Queensberry Grit ("Samson" is a boulder 20 ft×9 ft×8 ft at Bothel[78]), covers a coastal strip of the Lake District from the Solway Firth to Furness, its erratics rising to roughly 1000 ft (*c.* 300 m) in many places.[79] It is separated from the lower drift by sands and gravels,[80] as in the Solway area, at Maryport and in Furness. The southern limit, however, is only approximately known because the contending ice-masses oscillated as intermingled erratics evince; it extended, however, as far east as the upper end of Bassenthwaite Lake.

Tyne Gap and Edenside. Congestion in the Irish Sea compelled the ice from Dumfriesshire (the outflow from Nithdale, Eskdale and Teviotdale) to cross the Solway south-eastwards. Together with the ice from the north-east Lake District, it filled the Vale of Eden to overflowing. It abutted upon the north-west corner of the Pennine Chain and streamed broadly over the divide into the Tyne,[81] invading Northumberland and carrying with it erratics from the Lake District (Borrowdale volcanics, Carrock Fell gabbro, Threlkeld quartz-porphyry, Armboth dyke quartz-porphyry and Skiddaw granite), Edenside (Penrith Sandstone) and Galloway (Criffell granite). Crossing the northern end of the Pennine Chain, it received their tributaries, e.g. the North Tyne Glacier, and deflected them into the common trend. On the north, it was united with ice from the Southern Uplands of Scotland. On the south, its limit, given by boulders of the Borrowdale volcanics and Eskdale granite and the Permian and Triassic matrix of its drift, falls eastward from 1800 to 1100 ft[82] (*c.* 550–335 m).

It has been held that a branch of the Solway ice coasted along the Pennine escarpment up the broad Vale of Eden, receiving important contributions from the Lake District on the west; cross striations in west Edenside and towards its head signify oscillations in the strengths of the opposing streams.

Progress on the south was barred by ice from the Howgill Fells, a local centre which was joined with that of Shap Fells, Boagh Fell and Wild Boar Fell,[83] and sent a stream north-eastwards over Stainmore. But recent investigations[84] have shown that the Scottish ice had access to Edenside at an early stage only; it then pushed southwards up the vale as far as Brough on Stainmore, carrying with it Scottish, Triassic and Carboniferous rocks. After a period of deglaciation, revealed by laminated, lacustrine clays in the Vale of Eden above the till and the tooth of an ox (probably bison) in sands and gravels at Appleby[85] (correlated with the sands between the Purple and Hessle boulder-clays of Yorkshire[86]), the vale was once more filled with ice. During this phase of the Main Glaciation, Cumbrian glaciers, discharging eastwards, occupied the vale to such a depth that the ice overflowed by the Lune Gap (1500 ft; *c.* 457 m) on the south and, with considerable velocity, the Stainmore Pass (1500 ft; *c.* 457 m) on the east. It overrode hills of 2200 ft (*c.* 670 m) on the edge of the Howgill Fells and crossed others of this altitude at the northern end of the Pennine Chain into the South Tyne valley, lifting boulders of St. Bees Sandstone 1000 ft (*c.* 300 m) above the parent outcrop. The Cumbrian ice cleaved along a line in the upper part of the Vale of Eden and moved northwards down Edenside and in a gigantic meander round the Lake District into the Irish Sea, accompanied on the north and eventually north-west by Scottish ice and taking with it erratic trains of the Threlkeld, Armboth and Carrock Fell rocks. The direct impact of the Cumbrian and Scottish ice caused a diamond-shaped flow over the Solway.[87]

East of Edenside, Lake District ice was confluent with native glaciers from the Crossfell Range. Fed in local cirques, e.g. High Cup Nick, these extended to a slight distance, at most 2 miles (*c.* 3·2 km), from the front of the hills and parted to north and south flanking the opposing ice.

The Edenside ice, as just noticed, escaped by overflowing the Pass of Stainmore—not the lower pass (which carries the main road and railway) but the northern pass (with Galloway erratics and Shap granite) and the middle pass (with Shap granite but not Galloway erratics[88]). Chains of drumlins sweep in wide curves out of Edenside on to the pass, with boulders of Shap granite in tens of thousands, as was first noticed by J. Hall in 1815[89]—W. Buckland[90] identified them at Darlington—and others, less numerous, of Galloway granites,[91] Borrowdale volcanic rocks, Carrock Fell gabbro, St. John's Vale porphyry, Penrith and St. Bees sandstones, Dufton granite, Whin Sill, Permian brockram and occasional Ennerdale granophyre. The brockram was lifted from 850 ft (*c.* 260 m) at the outcrop to 1800 ft (*c.* 550 m) on the pass in such numbers that they are common boulders on the Yorkshire coast. East of Stainmore the area of dispersal of the Shap granite erratics is broadened but the erratics are rare north of the Tees between Bishop Auckland and the coast,[92] though a large one has been found in the Tyne valley north of Alston Moss which must have travelled by way of the Tyne Gap.

North Pennine Chain. Pennine valleys which are closed on the west were a nursery for native glaciers without "strange" erratics. The Alston Block in the north Pennines, for example, nourished a system of glaciers, e.g. in South Tyne, Wear and Tees. The Wear Glacier was fended off parts of its bed by the Tyne Glacier on the north and the Teesdale Glacier on the south. Swaledale Glacier received only small accessions from extraneous ice. Nidderdale Glacier sprang from the slopes of Great and Little Whernside.

The north Pennines had several nunataks,[93] probably snow-clad, which are

wholly free from glacial deposits or glacially transported pebbles and are marked by deep weathering of the rocks. Of a total area of over 50 sq. miles (*c.* 130 sq. km), mostly above 2000 ft (*c.* 600 m), they included a few nunataks about upper Wharfedale, near the head of Swaledale, and the much larger ones of Crossfell and Mickle Fell.

Pennine valleys with open heads received influxes of ice from west of the range: they became dominant factors in the east, e.g. the Tyne Glacier in Co. Durham and the Tees Glacier in the Vale of York.

The Teesdale Glacier[94] took rise in the semicircle of hills about the head of the dale and east of the Crossfell Range. It coalesced with Stainmore ice from Edenside a short distance below Middleton-in-Teesdale where Borrowdale volcanic boulders first appear. In Lunedale and Balderdale, New Red Sandstone detritus from the Vale of Eden imparts a red colour to the drift. Stainmore ice with Shap granite boulders flowed over the whole of Lunedale on the north and Gretna on the south and shouldered the ice from upper Teesdale over to the north side of the valley. Teesdale ice spread thin drift up to 2000 ft (*c.* 600 m) where a well-marked moraine bounds it occasionally. It moved eastwards along the dale as is attested by a multitude of drumlins, by striae, e.g. on the Whin Sill, and by the carry of local erratics, e.g. Whin Sill erratics at Northallerton and with crinoidal limestone at Darlington.

The centre of ice-shedding south of Stainmore on Boar Fell and Wild Boar Fell and at the head of Swaledale, Wensleydale and Wharfedale[95] reinforced the Teesdale Glacier on the north and kept the Edenside ice out of the lower Pass of Stainmore. Its ice flowed on the west and south down Dentdale and Garsdale and invaded the lower parts of the Howgill Fells and the hills and valleys of north-east Lancashire—Dentdale ice split on the northern flanks of Ingleborough and sent some ice into Chapel-le-dale while most of it went into Ribblesdale. On the east, it initiated glaciers which flowed down the bigger valleys producing drumlinoid tails which trail down from the ends of the spurs between the tributaries. Swaledale and Wensleydale glaciers united over their common watershed, only a few snow-clad nunataks projecting,[96] e.g. Ramsden Pike, Great and Little Whernside, Ingleborough and Penyghent. Even lower Swaledale, contrary to earlier opinion,[97] was glaciated at an early stage,[98] its older gravelly drift escaping removal by the later ice in sheltered hollows and on the lee sides of tributaries.[99]

From the local centre on Cam Fell, which with other local ice buried the country up to about 2400 ft (730 m), the ice passed north-eastwards to Wensleydale, south-eastwards to the Wharfe Glacier, and south-westwards to the Ribble. Ice moving south-westwards from Ingleborough and Whernside was deflected around and over Bowland Fells into the valleys of the Hodder and Ribble.

Nidderdale Glacier[100] was self-contained: its moraines consist of the local Millstone Grit and Yoredale rocks. Wharfedale Glacier flowed eastwards from its head (striae occur on the Cow and Calf, Ilkley) and received accessions from Ribblesdale in the west since there are drumlins on the parting between the dales and Silurian erratics in upper Wharfedale.[101] It was confluent with the Aire Glacier on Rumbles Moor to the south and entered the transverse valleys of Guiseley and Yeadon.

The Aire Glacier was a powerful overflow of western ice, largely from the Ribble. It moved along the valley, striating the rocks, as near Bingley,[102] depositing its boulder-clay east of projections and its erratics, e.g. Carboni-

ferous grit, limestone and chert, Silurian rocks from Ribblesdale, as near Skipton and at Bradford, and Lake District erratics, such as granite and Borrowdale volcanic rocks. The limit of its drift declines continuously at 60 ft/mile (1:88) from 1400 ft (*c.* 427 m) on Boulsworth Hill to 200 ft (*c.* 60 m) at Newlay near Leeds.

The Pennine valleys yet farther south, with the single exception of the Colne,[103] nourished no indigenous ice. Thus Calderdale with its tributaries was ice-free except near Todmorden[104] and part of the south Pennine Chain was a nunatak (see p. 776).

Northumberland and Durham. The Cheviot Hills, crowned possibly by a small local ice-cap[105] or by half-consolidated firn—the drift in the centre of the massif is purely local—came under the influence of ice off the Southern Uplands, which diverged in front of the Cheviots and crept round the flanks to meet again in the south-east.[106] The remarkable absence of Cheviot granite in the Yorkshire drifts, where the porphyrites are extremely abundant, suggests that the higher ground underlain by granite was not overridden by the extraneous ice.[107]

The earlier ice of the eastern north Pennines, following an interval long enough to allow of some weathering of the Scandinavian drift (see p. 749), flowed nearly coincidently with the local topography. It passed down the Wear and Tyne to the coast, striating the surface and depositing a blue clay about Teesmouth, in the lower Tyne valley and in Weardale. It afterwards came under the sway of the northern ice. Winding eastwards along its valley, the Tweed Glacier was turned south-eastwards across the northern end and along the eastern shoulders of the Cheviot Hills. It proceeded coastwise as a buffer-stream between Pennine glaciers on its inland side and the Forth ice on its outer flank which carried Lammermuir erratics southwards and St. Abbs porphyry to Tynemouth.[108] The Tweed ice, bearing Silurian greywacke, quartz and chert and Cheviot porphyry, caught up Lake District and Galloway erratics from the earlier Tyne ice and incorporated them in the Durham drifts so that an east Scottish-Cheviot drift with a high percentage of Cheviot material succeeded the western drift[109]: a well-defined boundary fixes the line of contact of the northern Tweed-Cheviot ice with the western Lake District-Tyne ice. The supposition has, however, been made[110] that the upper, red and purple clay, with far-travelled erratics of Tweed and northern origin, is merely the englacial detritus of an ice-sheet whose ground moraine is represented by the grey or bluish clay of local material and westerly derivation.

The ice proceeded along the coastal belt of Northumberland and Durham in a direction which gradually approached the south; over the Farne Islands it was east-south-east, in northernmost Northumberland south-east, and between Belford and Bamburgh nearly south.[111] The ice passed off the land between the mouths of the Coquet and Tyne and after describing a great curve came in again about Roker, striating the rocks at this place from the sea[112] and dredging up worn flints and broken shells from the bed of the North Sea.[113] It carried boulders of Whin Sill in great profusion southwards from the outcrop and the erratics of Magnesian Limestone which, setting in south of Tynemouth,[114] increase in Durham at the expense of those of Carboniferous Limestone and Lammermuir Grit.

Vale of York. Tweed-Cheviot ice, flanked by Tyne ice on the west,

crossed Durham from the north—erratics and occasional striae give the direction.[115] It barred access to the coast to the Tees Glacier which had earlier laid down the lowest boulder-clay of North Cleveland containing Shap granite and its fellow-travellers. It compelled that glacier to cross the scarcely perceptible watershed between Bedale and Northallerton into the Vale of York[116] over which its reddish moraine-profonde was spread. This overflow lowered the divide, planed down the Magnesian Limestone escarpment north of Wetherby,[117] and rose to more than 600 ft (180 m) east of the Vale. Erratics from Durham and Northumberland have been traced as far as Upsall and Thirsk. Flints from the north-east were transported to Stockton-on-Tees, boulders from the Cleveland dyke[118] to places to the south-east and south-west, a solidary shell of *Pecten* to Thirsk,[119] and Lias *Gryphaea* to Darlington. Shap granite erratics were distributed widely over the Plain of York[120] as far west (with Whin Sill boulders) as a line running roughly through Bowes, Dalton, Richmond, Brampton, Bedale, Snape, Catterwick and Kirby Malzeard[121]—the most southerly occurrences east of the Pennine Chain are at Balby near Doncaster[122] and at Blidworth in Nottinghamshire[123] —with Borrowdale volcanic rocks, Carrock Fell gabbro, Whin Sill, Criffell granite and Permian brockram. Ennerdale granophyre has occasionally been found erratic, e.g. at Dewsbury and Wakefield.[124]

The Vale of York Glacier had apparently two stages, the first, corresponding to the Upper Purple Clay (see below), the second belonging to Hessle Clay time[125] when the ice was slightly less thick. W. S. Bisat[126] stated that the two horizons are an older, grey drift (Drab Series of Holderness) with Pennine and Shap granite erratics, and a later, reddish-brown boulder-clay with Cheviot erratics (= Purple Clay of Holderness).

Cleveland Hills. The Tweed-Cheviot ice impinged upon the northern face of the Cleveland Hills and mounted the northern moors; its force is shown by the bodily uplift through 150 ft (46 m) of a block 450 ft (137 m) by 11 ft (3·5 m) of the Main Seam of the Cleveland iron-ore[127] and its extent by the fringe of drift, especially thick in the several bays, that has diverted many of the streams[128] (see fig. 97, p. 496). Turned westwards into the Vale of York and eastwards along the Yorkshire coast,[129] it rose to 1000 ft (*c.* 300 m), scattering pebbles sporadically—the highest material is preponderantly Scottish, Teesdale rocks being exceedingly scarce—and constraining the marginal drainage[130] (see p. 1193). Above this limit, which fell to east and west from a fluctuating region of splitting, the Cleveland Hills were unglaciated[131]; the summit moor is strewn with loose, weather-worn blocks of the local Moor Grit; the escarpments retain their sharp outline; "strangers" are absent; and only a small percentage of its Mesozoic rocks are erratic in the coastal drifts of Yorkshire.[132] Local glaciers, though postulated,[133] were unable to exist in the relatively dry, easterly position; even farther west, about the Aire valley, the snowline was as high as 1700 ft (*c.* 518 m).[134]

Holderness and East Lincolnshire. The coastal plain of Holderness and its continuation south of the Humber is almost uniformly at about 100 ft (30 m): the Chalk Wolds and the preglacial cliff which bounded the preglacial "Bay of Holderness" limit it on the west. More than 20 miles (*c.* 32 km) broad near the Humber, it tapers northwards to Flamborough Head where the Wolds plunge into the sea, though in Lincolnshire the drift sweeps on to their top and round their southern end. This plain, bisected

by the Humber, was overriden by ice which came in from the coast. This is demonstrated by plucking in the uppermost Chalk on Flamborough Head[135] (from north), by contortions in the boulder-clays,[136] by the carry of erratics including masses of Speeton Clay on Flamborough Head and at Aldborough,[137] and by erratics forced into the Chalk along the edge of the Wolds.[138] Occasional striae,[139] as at Sandsend (N. 35° W.), Robin Hood's Bay (N.), Car Naze, Filey (N. 24° E.), Filey Brig (N. 20° E.), South Ferriby (E.) and a striated pavement near Withernsea,[140] also prove a movement along the Cleveland coast into Holderness with a tendency to sweep in upon the land.

The drifts and especially their pebbles exhibit a rich variety of "foreign" erratics,[141] including distinctive Highland rocks, e.g. schists from Perthshire, Leny grits and Ben Ledi grits, rocks from the Southern Uplands, e.g. Haggis Rock, Queensberry Grits and radiolarian cherts, and the trachyte of Eildon Hills, and such Cumbrian types as Borrowdale andesites and ashes, Threlkeld and Armboth-quartz porphyries, St. John's porphyry and Shap granite found as far south as Darlington and South Ferriby[142]—Forchhammer[143] referred some to Labrador. They show a threefold succession, recognised in 1868[144] and afterwards confirmed[145] in both Holderness and Lincolnshire, the three clays being identified in the first place by the colour and their ground mass and subsequently by their erratic contents.[146] The lowest member is the lead-coloured Basement Clay, formed by redistributing and reconstructing Jurassic clays (Lias, Kimmeridge and Speeton), which are virtually absent from the higher drifts, and Chalk, both red and white. The original bedding is locally still preserved though sheared with fractured fossils.[147] The lowest layers, the Sub-Basement Clay, have abundant shore-rounded pebbles and small boulders of Scandinavian rocks, e.g. rhomb porphyry, augite syenite and elaeolite syenite. Still lower tills, the under tills of R. G. Carruthers,[148] are known from borings at Kilnsea and Kirmington.

The Basement Clay is exposed in few localities, e.g. Dimlington, Bridlington, Selwicks, Filey Bay and near Burgh (Lincolnshire), and extends past Scarborough, Whitby and Saltburn north of the Cleveland Hills. It encloses in places marine shells wrapped up in masses of sand and clay up to 30 ft (9 m) thick and thoroughly kneaded together.[149] The shelly masses, first discovered at Bridlington by A. Sedgwick in 1821 ("Bridlington Crag") and later at Dimlington, Flamborough Head (South Sea Landing) and in Filey Bay, were because of their profusion for many years thought to belong to a Pliocene Norwich Crag *in situ*.[150] It was afterwards recognised that they were local lenticles or rafts that had been displaced[151]—hence the term "till-with-rafts" recently suggested for this horizon.[152] The shells, which include foraminifera, mollusca, ostracoda and echinoid spines,[153] are diverse in origin and depth and are crushed (though sometimes quite uninjured) and disposed in streaks and nests. Intensely arctic, the majority living no longer south of the Shetland Isles,[154] the shells represent the scrapings of a boulder-strewn glacial sea-floor, since they are occasionally scratched and notched and the associated boulders have not infrequently been bored by *Saxicava*, *Pholas* or *Clione*.[155] They may, however, have been picked up from a still earlier till.[156] Recent research[157] has shown that the upper part of this clay, the so-called "Upper Basement" or "Drab Series", a very persistent horizon in the drifts of Holderness, is distinct. It contains much hard chalk and black flint and

abounds in rocks from Scottish, Cumbrian and Carboniferous sources, together with Scandinavian erratics which alone characterise the underlying true Basement Clay. A bed containing moss (*Hypnum* sp.) has been found above the Basement Clay.[158]

The overlying Purple Clay, prevailing purplish-brown, is probably in part derived from New Red Sandstone marls flooring the North Sea.[159] Its lower layers are extremely chalky though large transported masses of chalk and Jurassic beds are lacking. Shelly fragments are few and Scandinavian erratics relatively scarce; such as occur were probably obtained from the Basement drift.[160] Numberless boulders of Carboniferous rocks, Whin Sill and Shap granite, Borrowdale lavas and other Lake District rocks prove that the clay was deposited by the Early Scottish-Cumbrian ice which poured over Stainmore Pass.[161]

The Purple Clay, which is separated from the Basement Clay by a denuded surface, with infilled ravines, and by the "Sewerby" and "Kelsey Hill" Gravels, overlaps this clay in all directions and extends beyond the scarp of the Wolds at Speeton (the Wold moraines at Burstwick and Kelsey are of this age[162]) to fill the ancient valleys north of Flamborough and rest on the chalk at Hull—its most westerly occurrence is at North Ferriby.[163] Nests of gravel and sand in both coastal and inland sections in Holderness and at Cleethorpes in Lincolnshire divide it into a Lower and an Upper Purple Boulder-clay, each it is suggested[164] produced by a separate glaciation.

The Hessle Clay, well developed at Hessle on the Humber, is usually 10–20 ft (*c.* 3–6 m) thick and divisible into a lower and upper Hessle Clay by a gravel band and weathered zone,[165] the product of an oscillation. Less tenacious and more earthy than the older clays, it has neither shells nor sea-bottom material and few if any Scandinavian erratics though its erratics, relatively small and sparse, are of distant origin. Porphyrites and Silurian greywackes from the Cheviot Hills and Tweed valley, its main constituents, show that the Scottish-Cheviot ice was its parent. It fills hollows in the denuded surface of the Purple Clay and disappears on the north near Bridlington where it oversteps the earlier drifts on to the chalk of Flamborough Head. It thins along the scarp of the Wolds—its limiting moraine is seen astride the Humber at North Ferriby and South Ferriby[166]—and in Lincolnshire clings closely to their edge and runs into the valleys furrowing their eastern slopes. It underlies the warps of Fenland[167] as far as Stickney and Sibsey where it makes an irregular ridge.

Wolds. The Yorkshire Wolds, like the Vale of Pickering north of them (where shelly drifts extend as far as Yedmandale), were not overridden though extraneous ice slightly overtopped the escarpment at Speeton and surmounted Flamborough Head. Outlying patches of sand and gravel and sporadic pebbles of quartzite (similar to those of the Sewerby beach and of the Cleveland moors), Carboniferous limestone and Cheviot porphyrites above the limit of continuous drift prove that the eastern slope was glaciated.[168] The ice-free ground, where low, as in the central valley of the Wolds,[169] was subject to flooding from the ice. Elsewhere, frost acted upon the impervious frozen ground, draping it with sheets of flint-gravel carried by thaw waters (see p. 1063), as below the lowest boulder-clay in the buried valleys of Flamborough Head.[170]

East Anglia. Of East Anglia it has been said that it were hard to tell whether its beds or its literature be the more confused. Though J. Trimmer and C. Lyell studied it and S. V. Wood and F. W. Harmer laid the foundations of our present knowledge,[171] it cannot yet be said that a completely satisfactory sequence has been established: good exposures are few and the drifts are often contorted. The succession of local horizons, not to be seen in any one section but perhaps most fully exposed near Trimingham, is usually said to be (*a*) Cromer Till and Norwich Brickearth with Contorted Drift, collectively called the North Sea Drift, (*b*) Great Chalky Boulder-clay, (*c*) Upper Chalky Boulder-clay and (*d*) Brown or Hunstanton Boulder-clay.

The Contorted Drift,[172] exposed in the Cromer cliffs ("mud cliffs" of older maps), is quite local, being confined to the Cromer Ridge[173] and extending from Happisburgh to Trimingham—the "Great Eastern Glacier" (see below) may have destroyed it farther south. It begins in an attenuated form in north Norfolk, appears at the base of the Pakefield and Corton cliffs, and thickens rapidly northwards, coming out in the cliff at Eccles whence it extends continuously as the uppermost bed to Weybourne; towards Cromer it rises to 200–300 ft (*c*. 60–90 m). This drift is a medley of chalk and marl (the former increases westwards until at Weybourne the drift is practically pure chalk marl) with black flint and soft chalk of local origin, brickearth, sand, gravel and Pliocene Crag, all intermingled and contorted. It is penetrated by pinnacles of chalk interpreted as sea-stacks[174] but more probably, as C. Reid stated, relics of ice-erosion.

The contortions, extraordinarily violent at Mundesley, Cromer and Sheringham, as described by Lyell,[175] but less so in the east, e.g. at Happisburgh, are associated on the iceward side with thrust planes, and sweep round and conform with the outlines of the large masses of enclosed chalk. All stages in boulder formation are traceable from incipient ridgings of the chalk surfaces to highly inclined folds which heightened pressure sheared off and drove into the till. G. Slater,[176] modifying Reid's subglacial theory, correlates these features with englacial bands which were deposited when the slowly moving ice was halted. The contortions, attributed to the deluge or earthquake waves,[177] to stranded floe-ice melting *in situ*,[178] to boulders dropped from drift-ice,[179] to grounding bergs[180] or coast and floe-ice,[181] or to decalcifications and slips,[182] were doubtless made by overriding land-ice[183]; the chalk in the disturbances is always local and the contortions were produced by great force and resemble those seen in modern glaciers (see p. 112). The ice advanced from the North Sea in a direction which though variable was from somewhere in the north; it gave the east–west strike of the folds,[184] the occasional shelly fragments[185] (*Cardium edule*, *Cyprina islandica*), and the Scandinavian erratics,[186] including rhomb porphyry, laurvikite, nordmarkite, cancrinite syenite (Särna), elaeolite syenite, quartz porphyry (Dalecaria?), Swedish granite, hornblende porphyrite (Oslo region) and sparagmite, and British erratics, e.g. Whin Sill and other dolerites, Cheviot andesites and monchiquite from East Lothian.[187]

A distinction is often made between Contorted Drift, which is transgressive and occasionally reaches the Chalk, and the underlying Cromer Till. The latter, which occurs also in inland localities,[188] as about March and at Ipswich, is at Cromer, the type locality, a stiff, dark-grey, chalky boulder-clay containing soft chalk of the East Anglian kind and suggesting incorporation of Forest Bed clays. From Happisburgh to Mundesley, it is separated into a lower and

an upper till by Mundesley Sands. Nevertheless, the distinction is difficult to sustain: it is one of condition rather than of age. In part, the Contorted Drift may belong to the North Sea Drift, in part to the Great Chalky Boulder-clay. West of Cromer, marly Contorted Drift passes laterally into Great Chalky Boulder-clay.[189] Some of the contortions may even belong to the Newer Drift (see p. 772).

J. D. Solomon[190] maintained that the Cromer Till belonged to a glaciation preceding the Contorted Drift since a period of erosion intervened before the Contorted Drift and the heavy minerals are distinctive. Baden-Powell[191] suggests that the ice-movements converged about this area between Cromer and Lowestoft and Ipswich and so partly produced the Cromer contortions.

The Norwich Brickearth, well seen around that city and generally in south-east Norfolk, extends over 350 sq. miles (*c.* 900 sq. km) but not in Essex or Suffolk (except in the extreme north near Beccles and Lowestoft). Possessed of constant petrological characters,[192] it forms a brickearth or sandy loam, with a distinctive yellowish-brown, buff or greyish colour and a gritty matrix containing 40–60% of coarse sand of Pliocene source. It shows a tendency to vertical jointing and a streakiness inherited from thrust planes in the ice. This brickearth may belong to the same phase of glaciation as the Cromer Till[193] since its position on the *Leda myalis* Bed–Westleton Sands–Mid Glacial sand complex is identical and the characteristic Scandinavian minerals in the underlying deposit increase as the junction is approached. Nevertheless, it forms part of Harmer's North Sea Drift,[194] for this is implied by its sporadic Scandinavian erratics (e.g. rhomb porphyry), and by its lack of Jurassic and Neocomian rocks and of the hard Lincolnshire chalk—any chalk it may have had has been dissolved out. It suggests sweepings from the bottom of the North Sea, including unconsolidated sands and clays of the Eocene and Pliocene.[195] Like the Contorted Drift, it may be the product of icebergs[196] or of an ice-sheet melting out in water.[197] It is possibly the equivalent of the Drab Series of Holderness[198] and the Oxford Plateau Drift (see p. 629). Some of the brickearths, as in the Sudbury area, are confined to valleys and represent the outwash of the oncoming Chalky Boulder-clay ice.[199] The drifts above the Cromer Forest Bed may be later than the Norwich Brickearth and possibly a local equivalent of the Chalky-Jurassic Boulder-clay[200] since the Cromer Till is neither decalcified nor weathered and contains rocks mainly of British types.

In east Norfolk and Suffolk, the sands associated with the North Sea Drift and in places underlying or interdigitating with the Norwich Brickearth are represented by Westleton Beds which rest on an eroded surface of the Pliocene Crags and spread as a broad belt from near Mundesley to Dunwich and Westleton. Representing the shingle or sand deposited on the shore of an encroaching sea that lay in front of the first advancing ice-sheet, their pebbles include water-worn and rounded flints and erratics derived, perhaps by floating ice, from the Ardennes. These Westleton Beds, as J. Prestwich[201] named them, contain no trace of life (unless the *Leda myalis* Bed or Bure Valley Bed are their equivalent[202]).

The Great Chalky Boulder-clay (recently often referred to as Lower Chalky Boulder-clay), which looms more largely in British geological literature than any other accumulation, overlies the members of the North Sea Drift wherever they occur but farther west rests on solid rock. In a cliff section at Corton near Lowestoft it reposes on interglacial gravels (Corton Sands)

overlying Norwich Brickearth (see p. 771). Its fan, radiating from the Fens[203] (fig. 141), underlies more than 3000 sq. miles (*c.* 7800 sq. km). Setting in south of Caistor and Market Rasen in Lincolnshire, it floors the strip between the Cliff and the Wolds as far east as Horncastle: occasional patches[204] prove that it formerly continued over the Lincolnshire Wolds and the Jurassic ridge in Lincolnshire and Rutland. It rises as islands out of the Fens and along their margin between Crowland and Wisbech. North of the Thames it spreads to an irregular line across east Essex and from Chelmsford

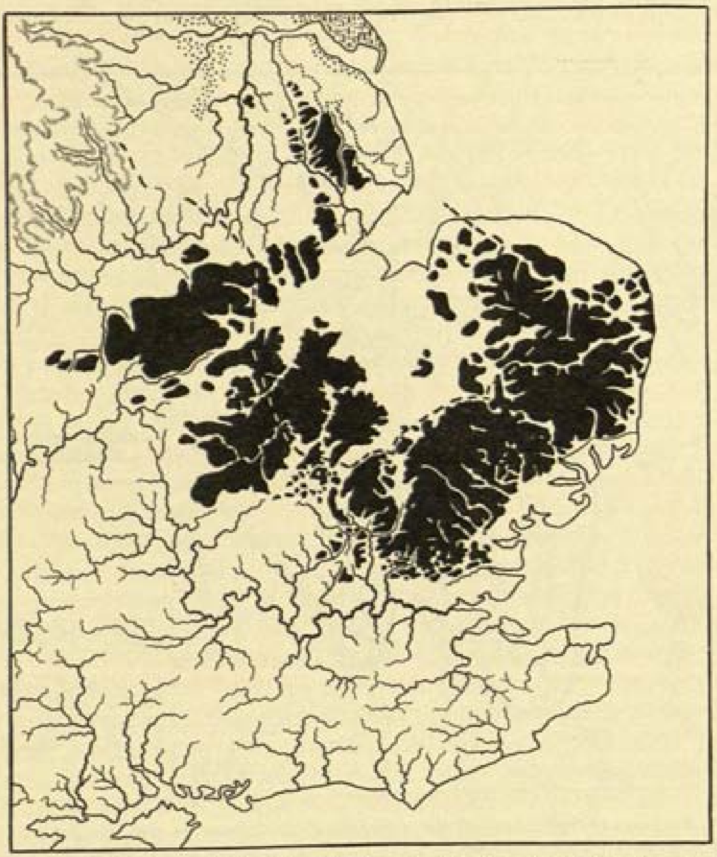

FIG. 141.—Fan of the Great Chalky Boulder-clay (in black) and boulder-clays farther north (dotted areas). S. V. Wood, *Q. J.* 36, 1880, map opp. 456 (part of).

westwards[205]—later river denudation has broken it up into irregularly shaped areas—and passes with its attendant outwash into the northern tributaries,[206] e.g. Colne, Blackwater, Lea and Rodney, and to a line running from Colchester, Maldon, Brentford, Hornchurch, Epping, Finchley and Hendon to Wembley Park[207] (North London). The outwash gravels of the Aldenham Lobe are traceable down the Colne valley and probably merged with the Winter Hill Terrace (see p. 997) at Gerrards Cross and Iver; those of the Finchley Lobe extend down the Brent.[208]

The edge then skirted the eastern end of the Dunstable Downs and locally and east of Hitchin overtopped the scarp of the Chiltern Hills and penetrated

certain of their valleys, e.g. Stevenage Gap. Spreading behind these hills westwards to St. Albans, it passed by Luton, Dunstable and the Vale of Aylesbury into the drainage basins of the westward flowing rivers, e.g. Avon and Severn, by Coventry, Nuneaton, Abbotts Bromley, Sudbury, Burton, Chellaston, Stanton and Nottingham. As the Eastern drift of the Midlands, where it is somewhat later than the Western Drift (see below), it extended westwards to a line which follows the high ground east of the Warwickshire coalfield and swings thence by Tamworth to Alrewas in the Trent valley[209] where the later Irish Sea Drift overlaps it. A tongue probably descended to the vicinity of Tewkesbury[210] (fig. 142) in the Avon and supplied material to

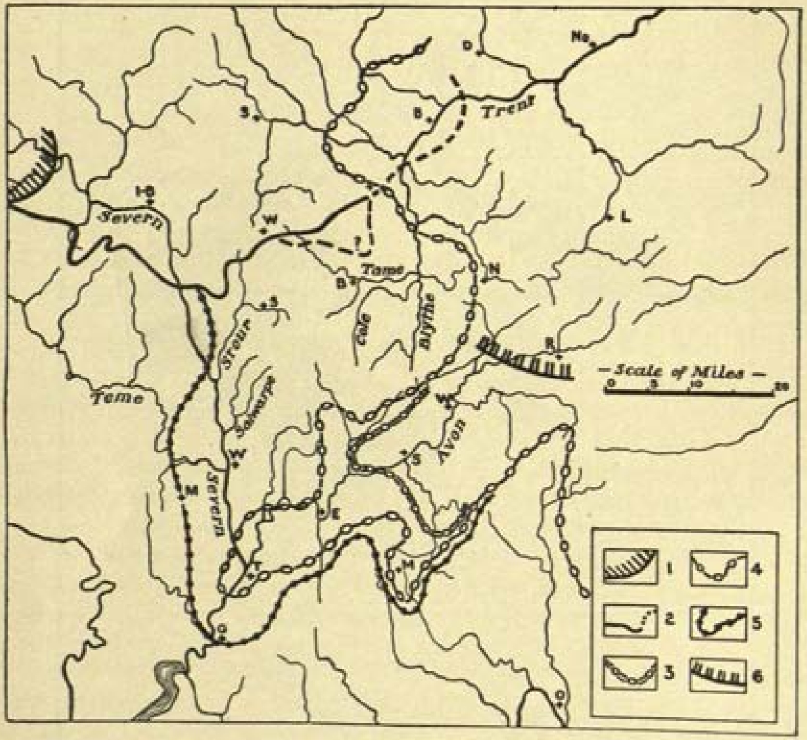

FIG. 142.—Spheres of influence of the successive glaciations in the Midlands. 1, Little Welsh glacier or "Welsh Readvance"; 2, Main Irish Sea glacier; 3, Stratford stage of, and 4, supposed maximum of Great Eastern glacier; 5, maximum of First Welsh glacier; 6, possible southern limits of a very early Eastern glacier. L. J. Wills, *1815*, p. 76, fig. 2.

No. 5 terrace of this valley (see p. 1005). In this western region, the drift has Triassic material as its common constituent.

If the drainage from the ice escaped freely, as north of London, in Essex and south-east Suffolk and in parts of Gloucestershire, sands and gravels and well-laminated brickearths were spread out as outwash[211]; the glacier-streams shifted the course of the Thames southwards from far north of the centre of the basin[212] (see p. 997). Below the stretch from Reading to the mouth of the Colne where the river maintained its course, the river was shifted from its original line through the Vale of St. Albans to a course through gaps near Watford, past Harrow and Finchley, the two lines converging at Ware to pass

through Essex into the Blackwater. Elsewhere, the melt-waters were pent up in extraglacial lakes,[213] e.g. in south-east Warwickshire at *c.* 400 ft (*c.* 120 m), the Vale of Belvoir, Soar basin, about Ware, Hertford and Harpenden, in the Tame basin, and along the Chalk escarpment near Tring Gap (see p. 1189).

The Great Chalky Boulder-clay, unlike the Cromer Drift, has relatively little igneous and distant detritus and few shells. Instead it has much hard chalk and Mesozoic material and "fossils from nearly every Secondary formation in England",[214] including *Cardinia* from the Lias, *Gryphaea* from the Lias and Oxford clays, and belemnites and ammonites from the Lias, Oxfordian and Kimmeridgian. Its rich assortment of English erratics, exemplified by analyses from Cambridge,[215] contains (besides local rocks like Hertfordshire Puddingstone, common in north-east Essex) Leicestershire granophyre (at Stockton, Moreton-in-the-Marsh—with Bunter pebbles, Lincolnshire flints and Carboniferous Sandstone—and at Stratford-on-Avon),[216] Hunstanton Red Rock (at Finchley, Muswell Hill and Ely and—with Lincolnshire Carstone—at Cambridge), Lincolnshire rocks, e.g. Chalk flints (at Rugby), Red chalk (Rugby, Cotswold Hills, Middlesex), Spilsby Sandstone (Northampton, Hertford, Lowestoft, Thorpe, Downham, Stowe, Ely, Letchworth, i.e. south-eastwards over Norfolk and north-west Essex) and Carboniferous boulders (Finchley). The minor Scandinavian element in Cambridgeshire and Hertfordshire represents remnants of the ploughed up Scandinavian drift, of which no other trace is left in these areas[217] (cf. p. 749).

The great variety of the more distant constituents is also well exemplified at Cambridge which has yielded the following[218]: Buchan Ness porphyry, Peterhead granite, Angus porphyry, North Berwick orthophyres, teschenites from Forth valley (?), limburgite from Haddingtonshire and Dufton granite from the Vale of Eden.

The boulder-clay resembles the underlying rock in composition and colour: on the Triassic Marls, e.g. south of Nottingham, it is red and encloses Bunter pebbles; east of the Trent, it is largely derived from the Lias; at Melton Mowbray, it is composed of local Oolitic limestone; in the valley of the Ouse it is often indistinguishable from Oxford Clay and has numerous *Gryphaea dilatata* and *Belemnites oweni*; on the Kimmeridge Clay it attains its darkest colour; near Bourne it resembles the Gault; and on the London Clay it is blackish or brown and sometimes has only been reconstructed.[219]

Harmer[220] recognised this change in the nature and erratics of the boulder-clay as it crosses East Anglia and its relation to the outcrops of Mesozoic rocks over which the ice passed. He distinguished three belts; (1) Chalky-Neocomian Boulder-clay, grey in colour and well developed in mid-Norfolk and west and south-west Suffolk, with Lincolnshire erratics, e.g. Chalk (hard and grey), tabular flint, Red chalk, Spilsby Sandstone and phosphatic Neocomian Sandstone with *Terebratula rex*, etc.; (2) Chalky-Kimmeridgian Boulder-clay, dark blue and tough, with large septarian nodules, fossils and boulders of Kimmeridge clay in west Norfolk and sharply delineated in Lincolnshire and East Anglia; and (3) Chalky-Oxfordian Boulder-clay, stiff and dark coloured, with a matrix of Oxford Clay and Oolitic debris. This clay, which may be grouped with the previous one as the Chalky-Jurassic Boulder-clay[221] but is sharply marked off from it, follows the Oxford Clay strike, extends up the Ouse, and is well developed south of a line from Bury St. Edmunds to Ipswich. The junction between the Chalky-Neocomian and the Chalky-Jurassic Boulder-clays is well seen in the cliffs at Scratby, 5 miles

(8 km) north of Yarmouth. The soils and live-stock industry are related to the variations in these glacial deposits.[222]

Although many writers derive the Great Chalky Boulder-clay from the North Sea and its chalk from the Wash[223] (which thus originated), others[224] refer its chalk to the Lincolnshire Wolds near which it is practically reconstructed chalk. They relate the Great Chalky Boulder-clay to an imposing glacier, Harmer's "Great Eastern Glacier"; this carried with it a characteristic garnet-epidote-amphibole assemblage and moved from northern England very slowly (because of its excessive debris and low gradient) and in contact with the North Sea Ice which influenced its course. In contrast to the earlier North Sea Ice which did not come in very far, it occupied all the country from Teesdale to Fenland and between the Pennine Chain and the Lincolnshire Wolds, crossing the latter over their whole length[225] or in places only.[226] It fanned out over the Fens, i.e. across the mouth of the Wash and to the east over Suffolk, south-east into Essex, south to Finchley and St. Albans, and to the south-west over the broad plains of the Nene, Welland and Ouse. It was guided by the Chalk escarpment to Hitchin and Bedford, as the similarity of the erratics shows,[227] poured through the Swaffham–Newmarket Gap,[228] flowed possibly to the site of the boulder-clay of the Cotswolds (with Millstone Grit, Carboniferous Limestone, Charnwood syenite, flints, chalk, red chalk and Bunter pebbles) at Moreton-in-the-Marsh,[229] an extreme limit of this ice, and moved westwards up the Trent towards Chellaston.

Consonant with these contiguous ice-streams flowing along the several belts of drift are the course of the belts and their lines of demarcation; the striae occasionally noticed[230]; the isolated patches of drift, somewhat difficult to correlate, on the plains of Yorkshire and Derbyshire[231]—one occurs at Staincross near Barnsley (where it consists of a lower boulder-clay, mostly of local Carboniferous rocks with a few far-travelled stones, overlain by sands and warps and in turn by a higher boulder-clay with Shap granite, Armboth felsite, Threlkeld quartz porphyry and Lake District andesites and rhyolites), and the largest patch, one mile (*c.* 1600 km) long, at Balby near Doncaster, contains Lake District andesites, Threlkeld quartz porphyry and Eskdale and Shap granites[232]; the Lake District material around Nottingham[233]; the occasional erratic Shap granite in East Anglia,[234] e.g. at Catton in Norfolk; the ubiquitous erratics of Carboniferous Limestone from the Pennine Chain[235]; the erratic trains[236] which spread to the south or south-east from the igneous outcrops of Markfield (Leicester, Market Bosworth, Aylestone), Mount Sorrel (Thursby, Leicester, Oadley, Ridgeway, Stockton, Aylestone, Coventry, Ragdale, Ingarsby), Groby (Market Bosworth, Aylestone), Breedon Hill (Leicester) and Nuneaton diorite; the Spilsby Sandstone train in west Norfolk from the Wash to Thetford, into central Suffolk and west of Barlow in Cambridgeshire[237]; the Hertfordshire Puddingstone found south-east of its outcrop; the phosphatic nodules uplifted from the base of the Chalk escarpment between Newmarket and Hitchin[238]; the huge boulders of Marlstone which trail for 12 miles (*c.* 20 km) from the escarpment west of Grantham[239] (see p. 364); the limonite gathered from the Lincolnshire Carstone[240]; the predominantly grey (Lincolnshire) flints; and (according to Harmer) the southern boundary of the Cromer Drift which runs from Dorking via Fakenham to Norwich[241] (south of which the Great Eastern Glacier ploughed out the earlier drift).

Harmer's work, the basis of all later researches, suffered from two defects,

viz. the postulate of cross-currents and the failure to recognise that there were two chalky boulder-clays, a later one in the belt of country from Kings Lynn to Ipswich (see below).

The ice of the Great Chalky Boulder-clay left on its retreat trails and fans of sand and gravel, including the older "Cannon Shot" gravels.[242] These ferruginous gravels, which consist chiefly of rolled and much-battered flints, poorly graded, with chunks of Chalky Boulder-clay in places, cap hills and plateaux in Norfolk and Suffolk and fill the valleys; they probably represent the outwash of the Chalky Boulder-clay ice.[243] This ice also left occasional lake-like areas, often several square miles in extent, in which laminated clays and loams accumulated, as at Hoxne, Hitchin and Ipswich (Foxhall Road). Decalcification of the tills has given rise to much of the sands of Breckland[244] (see p. 1437).

Under the Great Chalky Boulder-clay in Hertfordshire, Bedfordshire, Buckinghamshire and Leicestershire and occurring in broad sheets and flat sandy heaths associated with well-wooded estates over much of Essex, east Norfolk and Suffolk are the "Middle glacial sands and gravels" of S. V. Wood,[245] the "Corton Sands" of Baden-Powell and Reid Moir.[246] These white, grey or buff-coloured sands which change rapidly in thickness and are up to 70 ft (21 m) thick in mid-Norfolk and more than 50 ft (15 m) in east Suffolk, are current-bedded and occasionally ripple-marked and show strong selective deposition. Their grains are clean, sharp and angular and often indurated by infiltration into irregularly shaped masses. The associated loams are homogeneous and finely laminated, and the gravels, of varying grade, are mainly of flint (black, fresh or iron-stained, battered or broken), with quartzites and far-travelled erratics, such as sandstones, hard chalk, Jurassic limestone and fossils. The fauna, as near Yarmouth, is marine and indigenous (see p. 992) and includes about 100 species of molluscs and ostracods: they include *Tellina baltica*, *Scrobicularia piperata*, *Mya truncata*, *Cyprina islandica*, *Cardium edule*, *Astarte borealis*, *Natica alderi*, *Littorina litorea*, *Turritella terebra*, *Purpura lapillus*, *Buccinum undatum*, *Scalaria groenlandica* and *Bela turricula*. *Bos* cf. *primigenius* has also been found.[247] In north-east Norfolk, the gravels may be largely Westleton Beds (see p. 766) in which the Norwich Brickearth occurs as lenses.[248]

A study of the fauna and of the mode of deposition of the Corton Sands near Cromer suggests a succession of beaches piled up to at least 80 ft (24 m) above sea-level, though the movements which created the famous contortions at this place make it difficult to judge the original amount of submergence.[249]

The later glacial phases in East Anglia are not yet reliably established. Many investigators[250] have suggested that there were two chalky boulder-clays and recent opinion seems to support the suggestion. The Upper Chalky Boulder-clay of Boswell (= Upper Chalky Drift of J. D. Solomon and Gipping Boulder clay of D. F. W. Baden-Powell), which is centred about the Wash, is stratigraphically and lithologically distinct from the Chalky-Jurassic Boulder-clay and is seen sporadically in Norfolk and Suffolk (as far south roughly as the Essex boundary), for example, in Breckland and at Hoxne, Ipswich, Mildenhall (High Lodge) and Stowmarket. It consists mostly of a pale, sandy and chalky matrix enclosing pebbles of chalk, flint (including the "basket work" type), Red Chalk, Bunter sandstones and quartzites, Old Red Sandstone porphyrites, with an occasional erratic derived from earlier drifts[251]—the Cannon Shot gravels around Kings Lynn and

north of March have been regarded as its outwash.[252] This drift has usually been interpreted as a later and separate deposit,[253] or as a weathered layer of the Chalky-Jurassic Boulder-clay. Solomon[254] thought it represented the englacial material of this ice. The independent existence of this glaciation has still to be established, for while the mature soil profile at Ipswich[255] (Bolton's Pit) seems to confirm its existence, this "lateglacial drift", as about Cambridge and Saffron Walden, may be merely a product of nivation or solifluxion.[256] "Advanced" Clactonian occurs in the brickearth at High Lodge which lies between two boulder-clays (Great Chalky Boulder-clay and Upper Chalky Drift?).

Baden-Powell[257] stated that while the Great Chalky Boulder-clay glaciation crossed East Anglia from the north-west, the Upper Chalky glaciation was from Lincolnshire and the north and was bounded on the east by the Cromer Ridge and a front which ran from Quidenham by Hoxne to Ipswich, east of which lie its outwash, the Cannon Shot gravels. According to him the igneous rocks in the Chalky Boulder-clays were brought by this and not by the Great Chalky Boulder-clay ice.

The gravelly Cromer Ridge, a glacial protuberance[258] of typical kame and kettle topography and morainic structure, has an average width of 4–5 miles (*c.* 6·5–8 km); it runs for 20 miles (32 km) W.S.W.–E.N.E. from Holt to Trimingham 2–5 miles (*c.* 5–8 km) south of the coast and rises to 300 ft (*c.* 90 m). It is composed chiefly of violently contorted gravels and some boulder-clay, the core being Contorted Drift overlain by sands and gravels characterised by much pale grey angular flint, similar to that of Lincolnshire. It may be a terminal moraine of the North Sea Ice[259] ("Little Eastern Glacier"), and since it limits the contortions in the North Sea Drift[260] was probably made by a readvance, that of the Upper Chalky Drift[261] or the Newer Drift[262]—the uncontorted gravels spreading southwards from the ridge form its outwash deposit. The mounds and ridges, e.g. the eskers of Blakeney, Morston and other places, and the later Cannon Shot Gravels are outposts[263]; these gravels interdigitate with the Upper Chalky Drift and contain unrolled implements[264] of Clactonian and Acheulian and a mineral assemblage referable to Neocomian and Jurassic sources.[265]

The Hunstanton or Brown Boulder-clay,[266] which has practically no chalk, is later than the March–Nar Sea[267] and at Morston overlies an ancient shingle beach 10–25 ft (3–8 km) A.S.L. separating it from the Upper Chalky Drift. The dominant erratics are dolerites, dark blue greywacke grits and Cheviot porphyrites, with characteristic heavy minerals including pyroxenes in the earlier members of the succession. This clay is later than the Cromer Ridge and belongs to the Hessle Boulder-clay of Lincolnshire and Yorkshire, this correlation being established by the extremely similar petrological content and by the identical relation to the underlying marine gravel (Kelsey Hill Gravel, Hunstanton Gravel). At this stage, the ice just touched the north coast of East Anglia between Hunstanton and Morston—the clay also occurs at Happisburgh. While this ice may have shaped the Cromer Ridge[268] as its terminal moraine (though the materials may belong to the period of the Upper Chalky Drift) it is more probable, since the erratics and heavy minerals of the Cromer Ridge differ from those of the Hunstanton Boulder-clay, that the Ridge is not the terminal moraine of the latter[269] but is earlier and belongs to the Upper Chalky Drift (see above). This conclusion is confirmed by the raised beach or marine phase which separates the two deposits.

In East Anglia there appear to be four glaciations: the North Sea Drift glaciation; the Great Chalky Boulder-clay glaciation of Boswell (= Lowestoft Boulder-clay of Baden-Powell, Great Eastern glaciation of Solomon); the Upper Chalky Drift glaciation (= Little Eastern glaciation of Solomon); and the Hunstanton Boulder-clay glaciation. Uncertainty, however, still exists about the reality of all three later glaciations, namely, the Upper Chalky Drift, the Cromer Ridge and the Hunstanton Boulder-clay. Actual superposition of the three boulder-clays in one section has yet to be discovered. It seems likely that there are at most only two, namely the Upper Chalky Boulder-clay with the Cromer Ridge, and the Hunstanton Brown Boulder-clay.

Local Welsh Glaciation. Wales was enveloped in local ice. In the north, the mountains of Snowdonia, Arenig, Berwyn, Harlech Dome and Cader Idris range, many of which have very fine cwms, served as a powerful ice-radiant.[270] A southerly or south-easterly flow from Cader Idris and the Aran Mountains is testified to by numerous erratics of Ordovician volcanic rocks which are dispersed to beyond the Dyfi valley on to the hills south of Barth. On the east, striae point to the Shropshire plain down all the major valleys, e.g. Tanat, Ceiriog, Llangollen and Vyrnwy. Summits over 2000 ft (600 m) were overwhelmed and local (Welsh) slates, grits and Carboniferous Limestone moved as erratics across the strike to near Oswestry. Arenig felsites in particular were dispersed over a quadrant on the east and north-east[271]; the northern boundary runs approximately by Chirk, Cefn, Ruabon, Wrexham, Mold and the eastern declivities of Halkin Mountain to Holywell and the Vale of Clwyd; on the east, they occur at Birmingham, Frankley Hill, Bromsgrove, the Clent[272] (to 900 ft: 274 m), Wrekin and Lickey Hills, Wolverhampton, Walsall and Rugeley. This High Level Western Drift caps much of the ground above 400 ft (*c.* 120 m) in central England.

A local Welsh drift, dark blue or grey in colour, is found in the Vale of Clwyd. This Arenig Drift of T. M. Hughes[273] is associated with a cognate series of striae radiating from Arenig Mawr as far as the Mersey estuary—this ice failed apparently to reach the lower Dee and the Wirral Peninsula—and with Arenig boulders which were transported to the summit of Moel Flammau east of the Vale of Clwyd, though many were trapped and came to rest on the slopes below. Where the ice passed over the Keele Beds the drift is red.

The Merionethshire valleys were filled with glaciers radiating from the Arenig and adjacent mountains of Moelwyn and Manod. All the valleys from Barmouth northwards were occupied by ice pouring westwards or south-westwards into the head of Cardigan Bay.[274] Here it coalesced with ice which had moved outwards from Plynlimon and other mountains. South of Machynlleth,[275] the north Wales ice ascended the slopes leading from the Dyfi estuary and spread for several miles inland nearly as far south as Aberystwyth.

The greatest ice-parting in South Wales was on the Brecon Beacons, Carmarthen Fans and the moors at the head of the Taff and Rhymney valleys.[276] Ice from the former flowed down the broad dip slopes of the Old Red Sandstone, surmounting the minor scarps of the Carboniferous Limestone and Millstone Grit but failing to overtop the unbroken escarpment of the Pennant Grit or Moel Mosyn which diverted it south-westwards along the Neath and Tawy and south-eastwards along the Cynon and Taff; the two

lobes re-united several miles beyond the obstacle. The Coal Measure uplands between the valleys were the source of local glaciers which moved southwards on parallel but generally separate courses.

In Carmarthenshire, the ice proceeded from the north-east, disregarding the physical features, as far as Pendine. It swept westwards along the Towy, Gwendraeth-fach and Gwendraeth-fawr valleys though manifesting a pronounced tendency to escape southwards where the relief permitted, as striae and the oblique transport of erratics testify. The Welsh ice reached the shores of the Bristol Channel, e.g. at Swansea Bay and about Cardiff and Newport, distributing erratics from the Brecon Beacons over Monmouthshire and Glamorganshire: the statement that ice passed down or along the estuary[277] has no supporting evidence.

From central Wales, ice discharged eastwards into the Upper Severn and its tributaries and southwards into the Wye, overflowing Clun Forest and reaching at least 1700 ft (520 m) in Radnor Forest. Ice from south-east Wales, in particular from the northern slopes of the Black Mountains and the headwaters of the Towy, Usk and Wye, streamed outwards to the marches.[278] All the valleys, except possibly the lower reaches of the Severn and Wye, were filled with ice; scattered remnants of this Welsh drift, unmixed with Irish Sea debris (as Murchison[279] observed), remain in isolated positions, notably at high elevations.[280] The Wye Glacier, emerging north-west of the Black Mountains, and augmented by transfluents from the high ground to the west, spread out in a great lobe over the Herefordshire lowland (see fig. 244).

Ice from Wales and the Midlands proceeded at some time to the Stour-Evenlode watershed (= Campden Tunnel Drift[281] and terminal moraine of this ice) and sent a broad tongue through Goring Gap and melt-waters into the Thames basin. Similar waters afterwards overdeepened the gorge and excavated a suite of parallel, marginal channels.[282] This "Western Ice" also laid down an old drift which caps the hills in Essex and contains far-travelled material from the west and north-west, e.g. large, unworn flints, Bunter and other quartzites and white quartz pebbles.[283] At an early stage, it carried Welsh boulders to the Chiltern Hills[284] and to the Moreton-in-the-Marsh district, and probably extended over the vales of Severn and Avon to the Cotswold escarpment.[285] Its materials are found derived in the gravels of the "Proto-Thames" from Marlow into Hertfordshire and Essex. The Welsh drifts in general meet the eastern drifts which came from the north along a north–south line through Derby, Tamworth, Coventry and Stratford-on-Avon.[286] Sections at Finchley in the Stort valley, in various places in Essex, and at Hertford and Ware show two boulder-clays,[287] a lower one from the west and a later one from the north.

Although the evidence is scattered and ambiguous, it seems that there were three Welsh glaciations.[288] The first glaciation went down the Severn to below Tewkesbury and probably beyond, and to Gloucester and the Cotswold Hills, overriding the latter at Moreton and proceeding to Goring Gap. It invaded the head of the Avon as far as Rugby and the Thames valley near Aylesbury and was coeval with the Pennine glaciation (see p. 776)—it preceded the Irish Sea Ice, as Murchison[289] recognised and is shown by the superimposed boulder-clays[290] near Shrewsbury, in the Vale of Clwyd, in Colwyn Bay and in the Lleyn Peninsula. A second, somewhat less powerful, glaciation extended to east Worcestershire and the Warwickshire plateau and was contemporaneous with the Great Eastern Glacier (see

p. 770) but was separated from the first by the "Jurassic gravels", etc. which near Stratford contain a tooth of an archaic form of *Loxodonta antiquus*. The third glaciation followed the Irish Sea Drift[291] (see p. 1200), e.g. west of the Ceiriog, south of the Dee and near Shrewsbury and Oswestry, and deposited a brown boulder-clay upon the outwash sands and gravels and upon coarse torrential gravels from the hills.[292] Two glaciations seem to be established for north-west Wales.[293]

Cotswold Hills. The Cotswold Hills were apparently overridden[294]: an occasional pipe filled with boulder-clay, pebbles of northern rocks, e.g. Red chalk from Yorkshire and Lincolnshire, and the absence of deeply weathered limestone seem to indicate this, though some of the pebbles may be due to earth-sculpture of much earlier date. Their ancient, high-level Plateau Drift, which is probably coeval with that of Oxford (see p. 629), has suffered greatly from denudation.[295]

Isle of Man. Lamplugh's West British Ice[296] which filled the Irish Sea overwhelmed the Isle of Man from the north-north-west, deviating locally because of the obstruction the island presented.[297] Clean ice overrode the higher parts which have a local rubbly drift[298] while the lower dirty ice plastered its drift thickly over the northern plain and against north-facing slopes. Marine shells and "foreign" erratics[299] from Scotland (Galloway granites, Queensberry Grit, Arran granite and pitchstones, Ailsa Craig microgranite, Dalradian quartzite and schist), Lake District (Skiddaw slate, Borrowdale lavas, Eskdale granite, occasional Shap granite[300] and Ennerdale granophyre[301]) and the floor of the Irish Sea (Permian and Triassic sandstones, chalk and flint) prove its derivation and source, while the trail of erratics from the Manx granites of Dhoon, Foxdale and Oatland give its direction.[302]

Eastern extent of Irish Sea Ice. The severe congestion in the Irish Sea, due to the peripheral local ice-caps and the glut of ice in the Firth of Clyde (see p. 749), found relief by fanning over north-east Ireland, by pouring through St. George's Channel, by sending offshoots through gaps in the Pennine Chain, namely, Tyne Gap, Stainmore Pass, Aire Gap and Dove Holes, and by spreading as a vast lobe into the Cheshire Gap.

The Galloway ice, which split about Ravenglass and proceeded southwards round Black Combe and over Walney and Barrow, prevented the Cumbrian ice from flowing freely out on the north, and forced it to escape in the main into Lancashire. This southerly flow over Lancashire athwart the mouths of the Pennine valleys, first noticed by R. H. Tiddeman,[303] is shown by striae,[304] by drumlins in the Kent valley,[305] by Shap granite erratics[306] in the Lune valley south of Tebay and in the Kent valley to Lancaster and sparsely in a curved line (marking roughly the confluence of Cumbrian and Irish Sea Ice) by Longridge to Whalley and Silverdale (this southerly dispersal may have been when the Scottish pressure was at its maximum[307]); by Furness haematite at Blackpool and Rochdale; by Carboniferous Limestone along the eastern shore of Morecambe Bay to Liverpool; by Clitheroe red rocks at Stoneyhurst; by the southerly and south-south-easterly carry of Ingleton Permian[308] and of Silurian rocks from Chapel-le-dale, Crummock and Horton-in-Ribblesdale; and by the variety of Cumbrian erratics found in the North Staffordshire coalfield[309]; they include Eskdale granite, Buttermere granophyre,

modification of Carrock rock with acicular augite, Skiddaw granite (?), Threlkeld quartz-porphyry (?), and Borrowdale breccias, banded tuffs and basic lavas.

In conformity with this movement is the dispersal of the boulders of Eskdale granite.[310] These ascended the Duddon valley for a slight distance, were lifted to more than 1000 ft (300 m) on the west side of Black Combe, and were spread over Lancashire from Heysham and Bootle across Morecambe Bay to between Preston and Longridge and southwards to Burnley, and were scattered over Cheshire, Shropshire to Little Wenlock and Longmynd (1050 ft: 320 m) and to the north Welsh coast, e.g. Minera Mountain (at 1450 ft: 442 m), Vale of Clwyd, Colwyn Bay, Anglesey and Moel Tryfaen—pebbles travelled as far as Wolverhampton and Stafford and in the Severn drainage to between Tewkesbury and Gloucester. In conformity too are the occasional boulders[311] of the Ballantrae lavas and tuffs from south-west Scotland, e.g. in the Liverpool district, and the boulders of Eycott Hill lavas which travelled round the Lake District from its north-eastern side.[312]

This Irish Sea ice, the recipient of an important tributary from the Ribble valley[313] which brought Carboniferous limestone, chert and Silurian grits, overflowed with local deviations Bowland Forest, Pendle Hill and Rossendale highland and abutted upon the western flanks of the south Pennine Nunatak[314] stretching southwards from the Aire Gap. The well-marked limit of the highest erratics slants very slightly from 1550 ft (472 m) at Bousland (south of the entrance to Aire Gap) to 1250 ft (381 m) east of Lancashire and Cheshire.[315] It inclines in the direction of the flow north and south of the Rossendale highland and towards the Cliviger Gap and into the Walsden Gorge, both of which drained east of Todmorden into ice-free Calderdale (see p. 1202).

Above the erratic limit, the Millstone Grit has preserved its kaolinised soil, its irregular ridge-crests and its numerous weathered tors.[316] Yet occasional patches of drift, with Cumbrian erratics, on the southern Pennines[317] prove that extraneous ice, hemmed in between the Welsh mountains and the Pennine Chain, poured over the eastern barrier almost entirely[318] and moved into the Midlands where it laid down the Older Pennine Boulder-clay[319] as far at least as Leicester and Birmingham. It has been thought that this ice and its contemporary from the north-east coalesced and oscillated in the Nottingham district and the northern Midlands,[320] alternatively that the western ice was slightly later since fluviatile material parts the two sheets.[321] It appears, however, that this old Pennine ice of the Older Drift was coeval with the second Welsh glaciation (see p. 774) and earlier than the Great Eastern Glacier[322] (see p. 770). The recently discovered lower till in the River Nene and Kettering area which is free from chalk and flint but characterised by Bunter and Jurassic erratics[323] may also belong to this phase (see p. 1013).

The Irish Sea Ice sent a mighty lobe into the Cheshire Gap from the north-west, overspreading the wide plain with a more or less unbroken sheet of drift. The direction is given by striae[324] on Bunter Pebble Beds and Keuper Basement Beds in Cheshire and Lancashire, at Hollington south of the Weaver Hills, and on the east side of the North Staffordshire coalfield; by terminal curvature and bruised pebbles half embedded in the rocks[325]; by folds in the drift[326]; by fragments of marine shells found as far south as Gloppa and Oswestry (see p. 630); by erratics (mainly fossils) from the Whitchurch Lias, traceable to Wolverhampton, Lilleshall and Ironbridge; by

abundant Cumbrian (e.g. Borrowdale andesite, Buttermere granophyre, Eskdale granite) and Scottish (e.g. Criffell granite) erratics, the latter mainly in the western, the former in the eastern half of the gap[327]—they were transported to the Wrekin and Church Stretton line of the Bridgnorth moraine (see p. 992), as G. Maw[328] early noticed, and in smaller numbers to Birmingham and Worcester.[329] A boulder of Galloway granite, 30 ft (9 m) long, occurs near Madeley in Staffordshire.[330] Arran granite also occurs occasionally, as at Liverpool.[331]

The invading ice turned the Welsh glaciers southwards to conform with its own movement. The line of confluence,[332] marked by erratics of Cumbrian and Scottish igneous rocks and by marine gravels and shells, runs from the east side of Halkin Mountain through Caergwrle and Minera, along the Lower Carboniferous escarpment and high ridge of the Cefn-y-fedw Sandstone—shells are found at 1167 ft (356 m)—to Llangollen, aslant the Dee, and by Ellesmere, Baschurch and the Wrekin. The latter, though possibly a local ice-centre as its dispersed boulders show,[333] was at one time overridden since northern erratics rest upon its summit.[334] The Irish Sea Ice did not invade ground much above the 1000 ft (*c.* 305 m) contour in the neighbourhood of the Longmynd[335]: it deposited the Low Level Western Drift of central England.[336] Towards the north, the line just sketched may be a median moraine between local and foreign ice.[337]

The Irish Sea Ice swept vast numbers of Welsh erratics out of its path but left a concentration of them in the strip of country extending from Bromsgrove over the Lickey Hills and Frankley Hill to Birmingham and Lichfield. Its southern limit runs by Oswestry, Whittington and Eardiston.[338] Farther to the south-east, it advanced a short distance down the valleys of the Severn and Worfe and entered those valleys which drain eastwards into the Tame and even into the Trent valley[339]—it advanced to south of Bridgnorth, north of Enville, south of Wolverhampton and south and east of Walsall.[340] South of this southern limit, which is generally marked by a great accumulation of boulders, there is in Shropshire a pure Welsh drift from the Tanat, Vyrnwy and Upper Severn valleys, though the Main Terrace of the Severn and Nos. 2 and 3 terraces of the Avon (see p. 1005) which belong to this glaciation[341] are built up of debris from the Irish Sea Ice: the Kidderminster Terrace of the Severn lacks these northern ingredients. Fluvioglacial streams also carried northern detritus from the ice at Church Stretton as far as Ludlow.[342]

Striae and erratics prove that the Irish Sea Ice skirted the north Welsh coast and invaded the Vale of Clwyd to deposit its reddish boulder-clay and gravels.[343] This Clwydian or St. Asaph Drift of T. M. Hughes,[344] derived largely from the Trias, contains marine shells and such Irish Sea erratics as Galloway and Eskdale granites, Buttermere granophyre, Lake District andesites and Ailsa Craig microgranite. Drumlins, as in its analogue the Vale of Eden (see p. 759), graphically portray the lines of flow[345]: they stream along the axis of the valley, especially between St. Asaph and Denbigh, and curve into the breaks in the Moel Flammau range, e.g. in the pass of Bodfari.

The Irish Sea Ice, which constrained the Snowdon ice to radiate to short distances only, except on the south,[346] was itself cleft on the north Wales coast as divergent striae near Conway and the carry of erratics reveal. The main mass parted near the Great Orme from the stream proceeding coastwise to the Vale of Clwyd. It swept over Anglesey from the north-east, engraving striae and transporting insular and "foreign" erratics,[347] the latter gleaned

from all round the northern half of the Irish Sea, including Eskdale granite, Ennerdale granophyre, Borrowdale andesites, Galloway granites, Ailsa Craig microgranite, chalk and flint. It invaded the first line of hills east of Anglesey, deflected the Llanberis Glacier to the south, and made the Menai country a zone of conflict and oscillation between the extraneous ice and that from the valleys of Llanfaerfechan, Ogiven and Llanberis; the striae are sometimes crossed and the mountain, insular and extraneous erratics are intermingled[348] —Anglesey was invaded for some 3 miles (*c.* 5 km) by ice from the mainland.

Farther south, the ice overrode the Lleyn Peninsula—the summit of Yr Eifl (1849 ft: 563·5 m) was possibly a nunatak—into Cardigan Bay; marine shells and "foreign" erratics (chalk, flint, Ailsa Craig microgranite, Eskdale, Arran and Galloway granites) occur over the peninsula west of Llanbedrog. It carried Lleyn erratics to Criccieth[349] and, with marine shells, to 300–400 ft (90–120 m) along the hills between Harlech and Barmouth and southwards as far as Towyn.[350] Farther south, the local ice, acting as a fender, filled Cardigan Bay except south of Aberarth where the Irish Sea Ice again encroached upon the land in west Cardiganshire.[351]

This vast lobe in St. George's Channel deployed between Cornwall and south-east Ireland; the drifts are shelly at St. David's and in Pembrokeshire and along the south Irish coast between Wexford and Co. Cork (see below). It flooded Pembrokeshire, save for possible nunataks,[352] from the west-north-west; striae,[353] crags and tails associated with igneous bosses, terminal curvature and erratics, e.g. local rocks ("spotted" diabase from Prescelly, diabase from St. David's Head) and foreign rocks,[354] e.g picrite and glaucophane-schist from Anglesey, Carlingford granophyre, Cushendall quartz-porphyry, Cushendun microgranite, Borrowdale lavas, Scottish granites, hornblende porphyrite from Castle Douglas, quartz-hyperites from the Loch Dee area and andesites from Ballantrae and Lendalfoot—all these establish the flow. The invading ice overrode, in great part at least, the Prescelly Mountains, crossed Carmarthen Bay, and went eastwards to Pencoed, where as at Rhossli Bay it was practically contemporaneous with the local ice,[355] and to the Vale of Glamorgan and Cardiff,[356] the most easterly occurrence of the Irish Sea Drift yet known in South Wales. The stones of the inner circle and inner horse-shoe at Stonehenge (which were erroneously thought to have been transported by the ice-sheet from the north[357] or derived by man from an erratic-strewn plain fringing the southern English coast[358]) were shown petrologically to be identical with the spotted diabase of Prescelly and banded spherulitic rhyolites from Pembrokeshire[359] which man had easily collected from among the erratics dislodged by the ice that passed over Prescelly Mountains.

The Irish Sea Ice, with the local Welsh ice, may for a short time have blocked the mouth of the Bristol Channel[360] and have formed a lake, since boulder-clay, with striated erratics (including some apparently from Scotland), occurs at Fremington in Bideford Bay, north Devonshire.[361] Erratics of Irish Old Red Sandstone and other rocks traced to within 20 ft (6 m) of the highest point of the Scilly Isles,[362] may represent its moraine-profonde[363] or, with striated surfaces, the results of floe-ice.[364]

3. *Ireland*

Invasion by extraneous ice. Scottish ice passing down the Firth of Clyde overrode north-east Ireland as J. MacAdam[365] first recognised. This

is indicated by striae and by the carry of local erratics,[366] e.g. the Fair Head, Slemish and Scrabo dolerites and Castle Espie limestone, and of Scottish rocks,[367] e.g. Ailsa Craig microgranite, Arran granite and pitchstone. This invasion, imagined by J. R. Kilroe[368] to have continued beyond the counties of Donegal, Mayo and Galway, was of much more moderate dimensions: its limits, fixed by the distribution of Scottish and Ulster erratics (mainly basalt, chalk and flint), ran roughly along Lough Swilly to Londonderry, along the northern and eastern shoulders of the Sperrin Mountains, and by Draperstown and east of Omagh to Slieve Beagh, Co. Monaghan.[369]

Farther south, the ice encroached upon the coastal strip between Dundalk and Dublin,[370] carrying with it chalk and flint, Silurian grit, Mourne granite, Antrim basalt and marine shells. It extended to 300 m A.S.L. on Saggart Hill 15 miles (24 km) south-west of Dublin, and therefore probably invaded the Central Plain for some distance.[371] South of Dublin, it intruded upon coastal Wicklow and Wexford to great altitudes[372]—extraneous material has been traced to 1763 ft (537·5 m) on Two Rock Mountain, Dublin, to 1480 ft (451 m) on Great Sugar Loaf, and as marine shells to 1273 ft (388 m) in the Killakee valley south of Dublin. Pebbles of the Ailsa Craig microgranite[373] are found in the drift with Triassic sandstone and glauconitic Greensand. Marine shells, Ailsa Craig pebbles and striae prove that the south coast was invaded as far west as Ballycroneen, Co. Cork.

Ivernian ice. Ireland, as stated in Close's classical paper of 1866,[374] was buried beneath local ice (Ivernian Ice-sheet of G. W. Lamplugh,[375] Midland General Glaciation of A. Farrington[376]) except possibly for an occasional projecting summit. Its radiants lay in the mountain clusters of the west[377] (Donegal, Leitrim, Mayo, Galway and Kerry) and on a much smaller scale in the Mourne Mountains[378] (lateglacial) and Wicklow Mountains,[379] especially on their eastern side. Here the early glaciation, as in Wales across St. George's Channel, was an ice-cap. Its drift is now thin and mature in outline and has badly weathered boulders. The mountain clusters did not govern the glaciation throughout the Ice Age, since at the maximum the control passed to an axis on the lowland stretching from Co. Galway to Co. Antrim.[380]

Donegal, perhaps the most powerful of the gathering grounds, was glaciated from an axis traversing the Glenveagh and Barnesmore Mountains[381]; countless striae, roches moutonnées and drumlins radiate from it and erratics of the Barnesmore granite are dispersed fanwise (fig. 143). The widely distributed erratics of Galway granite, ranging as far south as Mallow and Clonmel and to the Aran Islands in the west, establish the importance of the Galway centre.[382]

Ice from western sources crossed the Central Plain from the north-northwest as striae, drift-ridges and lakes show,[383] with deviations induced by mountain obstacles—the influence of the Wicklow Hills, for example, was felt possibly as far north as Maynooth.[384] It overrode Slieve Bloom, Keeper Hills and the north Dublin and Wicklow Hills, carrying Carboniferous Limestone from the plain up to 1000 ft (300 m) on the flanks of Slieve Bloom and to 850 ft (*c.* 260 m) on the western shoulders of the Wicklow Hills, and to 1200 ft (*c.* 360 m) on the northern shoulders which were exposed to the full force of the thrust.

The Ivernian ice coalesced with the Irish Sea Ice on the plains north of Dublin, the fluctuating fortunes of the contending masses providing

a complex series of drifts.[385] It pursued a southerly or south-easterly course from Ennis to Limerick[386] and over northern Co. Cork,[387] transporting erratics southwards from the Carboniferous volcanic rocks of Co. Limerick.

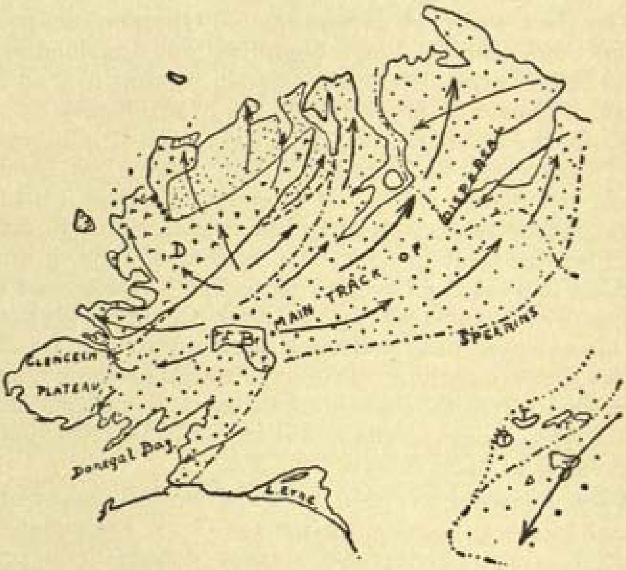

FIG. 143.—Fans of erratics of the Barnesmore granite, north-west Ireland. J. K. Charlesworth, *260*, p. 219, fig. 1.

The mountains of Kerry were the centre of a powerful radiation[388] which occupied almost 3000 sq. miles (*c.* 7800 sq. km) and filled the rias and even crossed them transversely. Glaciers covered western Co. Cork and crept eastwards down the great longitudinal valleys in confluence with ice on the north and east,[389] the whole country being buried, though with thinner ice than farther north and for a comparatively short time[390]: Close[391] thought the Comeraghs projected as nunataks and H. C. Lewis[392] imagined the flow was arrested by the Old Red Sandstone ridges. Kerry ice reached the south coast of Co. Cork and extended to the county's eastern limits where its characteristic boulder-clay, full of Old Red Sandstone rocks, rests upon the earlier northern drift. Its northern limit is unknown but may have run south of a line from Tralee to Cloyne.

Sligo and Mayo were glaciated by ice which swept northwards over the Ox Mountains to the coast in conformity with the striae and the transport of erratics of the Ox Mountain granite and the similar carry of boulders of Old Red Sandstone across the Carboniferous Limestone valley between the Curlew Mountains and the Ox Mountains.[393] This northerly movement is traceable as far south as the head of Clew Bay which the ice crossed.[394] Yet at one time the ice passed along the bay as striae, drumlins and marine shells in the Clare Island drift testify.[395]

The Scottish ice and the Ivernian ice met in Ulster and deflected one another about Lough Neagh to north and south[396] (fig. 144 B). Ice from western Ireland streamed over Slieve Gallion and down the Bann and flowed south-eastwards over Slieve Gullion, spreading fanwise over Lough Neagh

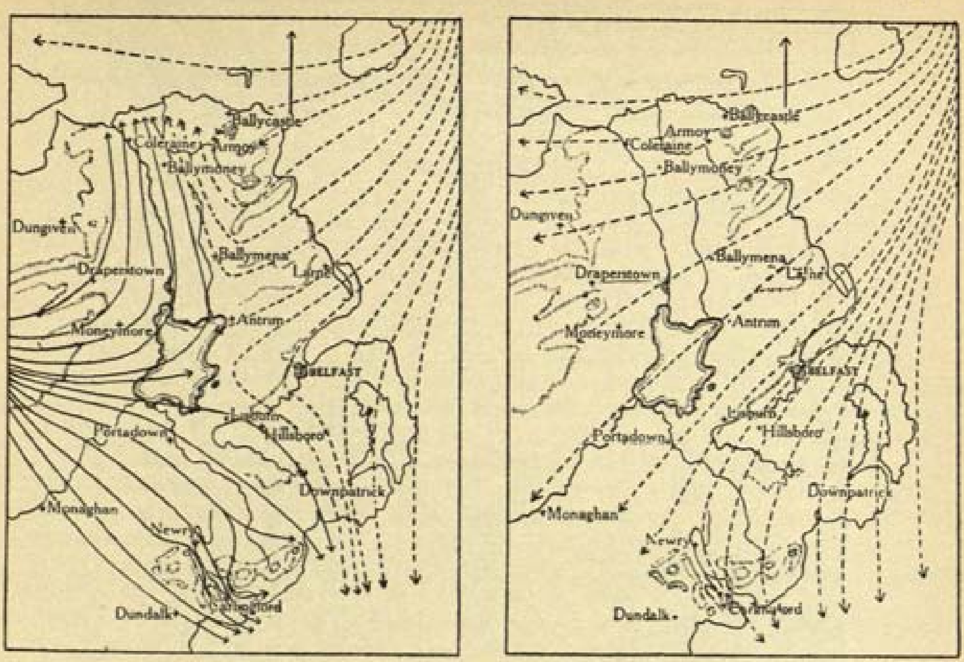

FIG. 144.—Lines of ice-flow over north-east Ireland at the period of Scottish glaciation (*right*), at the period of confluent ice (*left*). A. R. Dwerryhouse, *438*, p. 481, figs. A and B.

and carrying igneous and metamorphic rocks from Co. Tyrone to the valley of the Main, to the south-east of Lough Neagh and into Co. Down. The Scottish ice, which continued to flow southwards over Co. Down, was forced to move in a north-north-westerly direction up the Main to the north coast. The distributions of the drumlins (see fig. 252, p. 1212) and of erratics of certain distinctive local types clearly bring out this arrangement of the flow lines (fig. 145).

As on the borders of Wales on the opposite side of St. George's Channel, there are in the south-east unmistakable signs of a manifold glaciation. The earliest limestone-bearing drift (the "Limestone Gravels" of the Geological Survey), now largely destroyed by weathering and mostly only recognisable from the associated erratics, is found south of the Newer Drift (see p. 1208) and in the mountainous areas below the end-moraines. Within this line the ancient boulder-clay, much kneaded and contorted, underlies the newer boulder-clay and moraines: it is exposed in numerous coastal sections in Co. Wicklow and Co. Wexford.

The first of the three mountain glaciations recognised in the Leinster Hills —they are termed the Enniskerry, Brittas and Athdown glaciations[397]— probably extended from the Wicklow Hills to the east coast. It also spread from the Comeraghs and Knockmealdown Mountains to the south coast of Waterford where a red boulder-clay of local origin surmounts the marly boulder-clay of the earlier northern glaciation. Drainage channels and their deposits prove that the Brittas glaciation was roughly contemporaneous with the Eastern General Glaciation.[398]

That the Athdown glaciation of the Wicklow Hills was later than the Newer

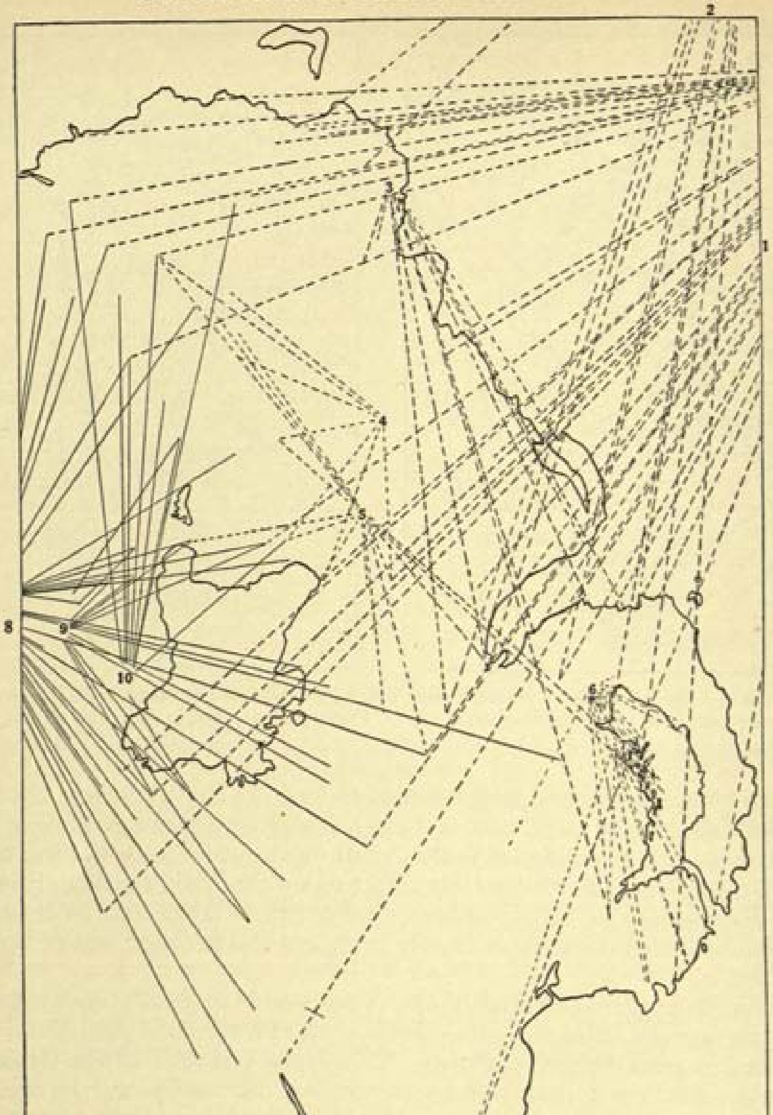

FIG. 145.—Distribution of certain erratic fans in north-east Ireland. 1. Ailsa Craig microgranite; 2. Arran Rocks; 3. Cushendun microgranite; 4. Slemish dolerite; 5. Tardree rhyolite; 6. Scrabo dolerite; 7. Castle Espie limestone; 8. Tyrone igneous rocks; 9. Carboniferous limestone; 10. lignite. J. K. Charlesworth, *269*, p. 258, fig. 2.

Drift on the plains, as the first was later than the first main glaciation, is shown by the occurrence of its moraines upon the Newer Drift in Glencree, Co. Wicklow and at Lockstown in the King's River valley, and by the behaviour of its drainage which escaped freely.[399]

The succession in the peat bogs at Ballybetagh and other places near

Dublin,[400] where a temperate bed is overlain by an arctic bed contemporaneous with the last Wicklow glaciation, suggests that the main Ivernian ice had withdrawn from the Central Plain before the onset of the local ice.

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CHAPTER XXXIV

PLEISTOCENE LIFE

1. Plants

The late-Tertiary flora shows the impact of worsening conditions in all quarters of the globe (see pp. 690–696). The floral zones migrated slowly equatorwards and the east Asian element was gradually eliminated in Europe (see p. 692). This elimination continued throughout the Pleistocene, as is shown by a comparison of the floras of the different interglacial epochs in Europe (see pp. 908–910), the British Isles (see p. 1383) and North America (see p. 1376). During the glacial epochs, the floras wandered southwards in the northern hemisphere and were modified (see pp. 1375, 1376). Asylums probably existed in both the Old World (see p. 1391) and the New (see p. 1392). Tundra occupied the periglacial zones outside the ice-sheets in Europe (see p. 1066) and to a less extent in North America (see p. 1068). Forests persisted in the Mediterranean region (see pp. 957, 1379). Floral changes took place in the pluvial zones of still lower latitudes (see ch. XLI).

During the interglacial epochs, and particularly during one period of complete deglaciation (see pp. 915–917), the flora re-occupied the glaciated lands. The order of immigration was in general that of postglacial time though there were certain minor differences (see pp. 908–910). Each interglacial epoch had a slightly different marine and plant composition (see p. 910).

On the final retreat of the ice the plants migrated polewards once more, the rate of spreading depending upon numerous factors (see p. 1425). The plants returned to the glaciated terrain in a definite order, as is revealed by the macroscopic remains and the pollen in the peats and other accumulations (see pp. 1438–1456).

During the postglacial climatic optimum many plants reached higher latitudes than now (see pp. 1484–1494) but were driven southwards in the northern hemisphere by the climatic worsening about 500 B.C. (see p. 1495). Equilibrium is seemingly not yet established (see p. 1498).

2. Invertebrates

The Pleistocene invertebrate life, which is preserved in stream, lake and marine sediments, and in loess, cave, tufa, scree and other deposits, has a history which in the main parallels that of the plants. The climatic worsening of the later part of the Tertiary era was recorded in a latitudinal shift of the marine shells (see pp. 696–699), and was followed by that of glacial times when land (see pp. 1378–1386) and marine (see pp. 1090–1092) shells were greatly displaced equatorwards and bipolarity among certain forms may have resulted (see p. 1086). These changes were accompanied by others which were produced by the to-and-fro movements of the sea-shores with the alternation of glacial and interglacial epochs (see p. 1355). During the warm interglacial epochs both land and marine shells re-occupied their previous areas and reached higher latitudes in both the Old World (see p. 914) and the New (see p. 916).

The lateglacial and postglacial changes in climate and geographical distributions of land and water were reflected in migrations of land and marine invertebrates (see pp. 1290–1313).

3. Mammals

Provenance. The investigation of the Pleistocene vertebrate fauna sprang from the search for unicorn's horn (*ebur fossile*), a supposed specific for many diseases. J. F. Esper examined the animals of the French caves between 1770 and 1790 and was followed in Germany by the brothers J. and R. Wagner. The exploration in Britain was initiated by J. Whidbey in 1816 and carried on by J. McEnery and by W. Buckland who applied to Kirkdale Cave[1] the lessons he had learned from G. A. Goldfuss in Bavaria. The study of British fossiliferous caves was continued by R. A. C. Godwin-Austen, G. Busk, W. Pengelly, W. B. Dawkins and W. A. Sandford while C. Lyell, J. Evans and J. Prestwich investigated the river gravels.

The animal remains, usually teeth, less frequently bones, are obtained occasionally from oil seeps and muds of salt springs, e.g. at the late-Pleistocene Rancho la Brea[2] near Los Angeles in North America (sabre-tooth tigers, wolves, elephants, ground sloths, camels, horses, tapirs, antelopes, deer, peccaries, rabbits, moles, bats; storks, peacocks, turkeys, eagles, vultures, condors), but generally from brickearths and river-terraces, from loess and especially from caves and shelters, most of which lay beyond the ice and its floods. The caves, which were more plentiful during Pleistocene than during the preceding Pliocene[3] (see p. 225), have been of the utmost importance in Europe but in America have furnished comparatively little information about Pleistocene life, partly because there were no cave animals (cave lion, cave hyaena and cave bear). The caves are almost invariably hollowed out of limestone, as in the Ordovician of Choukoutien, Peking,[4] Devonian of Kent's Cavern,[5] Plymouth, Brixton, Drachenhöhle,[6] the Harz and Moravia,[7] Devonian and Carboniferous in the Ardennes, Carboniferous in the Pennine Chain, e.g. Victoria Cave, Settle,[8] in Flintshire, Gower and the Mendips, Permian Magnesian Limestone, e.g. Creswell, Triassic dolomite of Wookey Hole,[9] Jurassic in Swabia, Jura, Kirkdale,[10] Wildkirchli[11] (Schrattenkalk), Kesslerloch,[12] Schweizersbild[13] (Malmkalk) and Ightham[14] (Kentish Rag) and Cretaceous in the Dordogne.

The remains are found in the white or cream-coloured stalagmite, grown under wet conditions by drip from the roof. It is coloured by earthy and ferruginous matter and is loose and friable in texture or, more commonly, hard, coherent and crystalline. Remains are obtained too from cave-breccias which, especially at the mouths of caves, consist of angular fragments detached probably by frost from the roof and walls and cemented together by carbonate of lime. Cave-earth, a tenaceous reddish loam laid down by flood waters charged with the silts of successive inundations, either intermittent or irregularly recurrent, has likewise served as a tomb, as have the water-worn gravels which have been carried into caves by subterranean or surface waters or the sea and have been frequently consolidated as a conglomerate.

The caves were often dens of cave hyaena and cave bear, the former occupying the caves all the year round, the latter only during the winter months.[15] The animals left an excessive number of teeth in ratio to the number of bones; they gnawed, fractured and crushed the bones of their prey, including young mammoth, in a characteristic fashion[16] which is exactly

comparable with that observed in modern zoological gardens; they scored the splints by their teeth and claws as Buckland[17] recognised; and they deprived the lower jaws of their angles, coronoid processes and lower borders.[18] Their fossil faeces or "coprolites"[19] build in places a greyish-white layer (*album graecum*) of calcium phosphate often flattened by tramping. The animals trod and polished the bones and floors and smoothed and polished the walls of narrow passages by rubbing their flanks against them.[20] Footprints[21] and the teeth of young hyaena and occasional foetal remains of the cave bear[22] confirm the occupation, as do the vast quantities of the remains and the "captivity diseases" of the cave bear,[23] which was the only animal in some of the caves of Bavaria and the Harz Mountains and at Mixnitz was apparently a herbivove.[24]

The Jermanowska cave (Poland) yielded *c.* 1000 bears.[25] Wildkirchli was also a bear den; for, excepting a few individuals of *Felis pardus* and *F. spelaeus*, the bones represent over 1000 bears and 99·5% of the total weight.[26] Similar figures from other caves[27] are Hohenstein, 98%; Charlottenhöhle, 99%; Hohlenfels, 95%; Cotencher, 95%; and Polotschnik cave (Karawanken), 99%. The bones of the remaining animals have either been washed into the caves[28] or have been carried in by predacious beasts—mammoth bones, for example, usually belong to young individuals[29] while hippopotamus is mainly represented by young adults or calves.[30] While A. Penck[31] wrote of an *Überschwemmung* of cave bears it is more probable that the density was no greater than that of a brown bear area to-day and that the animals were concentrated locally.[32] In general, a cave was occupied at one time by one or a few families only.[33]

Some caves served as domiciles of man (see ch. XXXV); ashes and carbonised bones are not infrequent, e.g. at Wookey Hole in Somerset, and the commonest bones sometimes are those serviceable to man, e.g. *Lepus timidus*, *Equus caballus*, *Rangifer tarandus* and *Lagopus*. Kesslerloch, for example, was inhabited from Mousterian to Magdalenian times.[34] Caves served too as places of human sepulture and of mural decoration (see ch. XXXV).

The abundance of the animals during the Pleistocene may be gathered from the following additional numbers found in well-known caves; Kirkdale,[35] *c.* 300 hyaenas; Hohenstein,[36] *c.* 400 cave bears; Polotschnik Cave[37] (east Karawanken), 1500 bears; Inchnadamph,[38] more than 400 reindeer; Peterfels,[39] 640 reindeer and 870 arctic hare; Gailenreuth Cave, 800 cave bears; Kesslerloch,[40] at least 500 reindeer and 1000 arctic and alpine hares; Tor Bryan cave[41] (Devonshire), more than 800 hyaenas; a "cemetery" of mammoths at Cannstadt; nearly 1000 mammoths at Předmost[42]; more than 3000 elephants in Swabia[43]; more than 500 mammoths dredged from the floor of the North Sea in 13 years[44]; 16,000 lemmings in the Balcarova cave, near Ostrov, Moravia[45]; more than 3000 reindeer in the Grotte de Gourdan[46]; and 100,000 horses on the Aurignacian station of Solutré.[47] The Drachenhöhle near Mixnitz[48] (32 km north of Graz) yielded remains of cave bear estimated at 9000–12,000 individuals (30,000–50,000 may have died here) and nearly 24,000 metric tons of phosphatic material, derived from faeces and from bones and animal remains, including bats. The prodigious numbers of bones of cave bears of one single species form one of the most striking biological phenomena of the Glacial period. The remains were of course accumulating during many thousands of years.

Nevertheless and in spite of the varied fauna known to us—the British Isles had at least 72 species of mammals besides birds, reptiles and amphibians[49]—they present but an imperfect picture of the whole Pleistocene life. Glacial faunas in particular are poorly represented while in judging the relative abundance of the various animals in the river gravels corrections have to be made for certain biological factors, such as the animal's mode of life, its amphibious habits, its custom to live in herds, and the size of the skeletons or of individual bones.[50] Fish have rarely been observed. Thus only ten species are known from the British Pleistocene,[51] including perch, pike, roach, dace, tench and rudd. Birds also are rare; this is exemplified by a list of British Pleistocene birds[52] and of birds from Mixnitz.[53]

Characteristics and Geographical Range

In these pages we are concerned not so much with osteology as with the light the mammals throw upon the climate and the physical and other changes of the times. Consequently, the description of the more important members of the fauna is based not upon a strict zoological classification but upon the climatic zones in which the animals lived, viz. (*a*) southern, (*b*) steppe, (*c*) tundra, (*d*) alpine and (*e*) climatically indifferent animals with great powers of adaptation and consisting of species still living, e.g. wolf, fox (S. H. Reynolds[54] described the fossil Canidae of Britain and Freudenberg[55] those of central Europe), details of which may be obtained from standard zoological text-books. Regional monographs on the Pleistocene mammalia of various countries, e.g. Britain,[56] Baden,[57] Hungary,[58] Russia,[59] Netherlands,[60] Denmark[61] and Iberian Peninsula,[62] furnish a valuable basis for faunal studies.

The Holoarctic fauna of Pleistocene North America and Eurasia was derived from common ancestral sources. Of eleven orders of Pleistocene continental mammals of Holoarctic distribution, eight were common to both hemispheres, the marsupials and edentates being restricted to the New World and the Primates to the Old World. The faunal differences become more apparent when the families are considered.[63]

(*a*) *Southern Mammalia* (*Faune chaude*)

The Pleistocene mammals include a number which W. B. Dawkins grouped together under the rubric "southern". This group, however, was for the most part not strictly southern in its origin; for some of its members were Asian and others, so far as Europe is concerned, were autochtonous and had persisted from the Pliocene. The truly African species, if there were any, may have entered Europe over land-bridges which offered an unobstructed passage for immigration from North Africa by way of Gibraltar and Sicily and from Asia Minor by the Aegean Sea and the Hellespont (see ch. XLIV).

This *faune chaude* included *Hippopotamus*, *Camelus*, *Rhinoceros*, *Elephas*, *Machairodus*, *Felis* and *Crocuta*. Although a few species, including *Hippopotamus amphibius* are still living, the majority are now extinct.

Hippopotamus. The Pleistocene *Hippopotamus*[64] was somewhat bigger than the living form of central and southern Africa. Cuvier[65] (1824), therefore, regarded it as an extinct species, *H. major*, and A. G. Desmarest (1822) named it *antiquus*. But the animal seems to have been specifically identical with *H. amphibus*[66] though later palaeontologists[67] have persisted in using the

term *major*, thereby implying the existence of two species. H. F. Osborn[68] named it *H. amphibius major*. Like *Crocuta crocuta* and the great cats it most probably originated in Asia since it was present in the lower Pliocene of the Siwalik rocks of India and made its first appearance in Africa (Egypt and Algeria) in the middle Pliocene.

During the Pleistocene, the hippopotamus in Europe had roughly the same or a slightly smaller range than *Elephas antiquus* and *Diceros leptorhinus* and, as mapped by Boule[69] (fig. 146), embraced that part of the continent west

FIG. 146.—Map showing the distribution in Pleistocene Europe of *Hippopotamus* (dash line = northern limit). M. Boule, *171*, fig. 19.

of the Rhine: it was rare east of that river and the Rhône-Saône, e.g. at Mosbach-Biebrich (near Wiesbaden) and in Lower Austria.[70] It was plentiful in river-gravels in England (a whole herd, with individuals of all ages, was discovered at Barrington, Cambridge[71]), as in the Thames and Severn, and went as far north as Kirkstall near Leeds (three individuals).[72] It was carried into the hyaena dens of Kirkdale, Pont Newydd, Cefn, Gower, Settle, Durdham Down, Kent's Cavern and Overton.

The hippopotamus inhabited a land provided with the rivers and lakes that are necessary for its dispersal. It wandered through Europe from the Mediterranean region by the Rhine and Rhône, less probably as Scharff[73] postulated, by the Jordan and south-east Europe. The animal was also fairly common in the Pleistocene of Java, central and north Africa and in Palestine and Syria.

Camelus. The camels arose in the upper Eocene of North America, passed though the Miocene stage of *Procamelus*, and migrated into Asia and south Russia during the Pliocene (*Paracamelus*) and into South America over

the central American land-bridge in the Pleistocene. They were widespread in North America[74] and had several species in the European and neighbouring Pleistocene. These included *Camelus alutensis* Stef. of Rumania,[75] *C. knoblochi* Nehr. of the Volga,[76] and those which wandered into Italy,[77] Algeria[78] (*C. thomasi* Pom.), Galilee[79] and west Siberia.[80]

Elephants. The Pleistocene elephants are of considerable interest to the geologist since their evolution, partiality to warm or cold climates, and gradual extinction confer on them zonal or chronological value.

The mastodont of the Pliocene[81] is distinguished from the elephants by a lower and flatter head and by simpler grinding teeth, never more than two at a time in use in each half jaw. The animal became extinct in Europe at the end of the period but survived into Pleistocene North America. Here it has been various called *Mammut americanus*, *M. ohioticus* and *M. giganteus*, and ranged widely and abundantly south of the ice-sheet,[82] especially in the forested region of the Pacific coast and east of the Mississippi. With the tapirs it extended into South America.

Skulls and skeletons of *Elephas* are extremely rare in European deposits; in England, for example, there has been found only one skull (mammoth) at Ilford and only one skeleton, minus the cranium (*E. antiquus*), at Upnor near Chatham[83]—a similar almost complete skeleton was found in Italy.[84] Molar teeth, on the other hand, are extraordinarily plentiful and establish an evolutionary series.

The evolution of the molars shows that the ridge plates are transverse ridges which have gradually become compressed and increased in number, and that the whole crown of the tooth has increased in depth. Hence, generally, the deeper the tooth and the greater the compression, the more numerous and the narrower the lamellae, and the wider the tooth, the later is a specimen's geological age: the number, compression and elevation of the ridge-plates increased as the primitive browsing habit developed into a grazing habit. The third or ultimate molar of *E. planifrons* had 11 ridge-plates, the most highly specialised grinders of *E. primigenius* (Siberian type) up to 29,[85] and those of *E. primigenius compressus* of Alaska 27.[86] As in the case of the rhinoceroses and the voles[87] the change was an adaptation to hard vegetation (the mammoth near its southern limit had wide-placed molars to feed on more succulent vegetation) or to the increased growth of the tusks.[88] The dentition of the Pliocene forms has been discussed by C. Depéret, L. Mayet and F. Roman,[89] and that of the Pleistocene species by several palaeontologists[90] including M. Pavlov[91] who described the Russian fossil elephants.

Before Falconer's differentiation in 1844,[92] all British Pleistocene elephants were referred to *E. primigenius*, aberrant molars being regarded as varieties only, as by Owen.[93] Falconer recognised three species, *E. meridionalis* Nesti, *E. primigenius* Blum. and *E. antiquus* Falc. A. L. Adams[94] adopted all three but emphasised their variability. H. Pohlig[95] showed that the "broad crowned varieties" of *E. antiquus* were intermediate both in form and age between *E. meridionalis* and *E. primigenius* and named them *E. meridionalis trogontherii* (= *E. armeniacus* Falc. according to Freudenberg[96]).

While the Tertiary and preglacial history of the *Elephas* ancestors has been well written by H. F. Osborn,[97] the Pleistocene evolution of the elephants is the subject of divergent views.[98] All agree that the three classical species no longer provide an adequate classification. Some think *E. antiquus*, *E. africanus*

and *E. meridionalis* belong to different genera,[99] others that *E. antiquus* was evolved from *E. planifrons*,[100] from *E. africanus*[101] (Soergel,[102] denying this, thought *E. africanus* was descended from some unknown *Stegodon*), from *E. meridionalis*,[103] or from *E. ausonius*[104] Forsyth Major of the Val d'Arno and other localities in Italy and France and the Norwich Crag of East Anglia, with a form transitional between the two in the Cromer Forest Bed.[105] Recent work[106] suggests that *E. africanus* evolved in upper Pleistocene from an *E. planifrons* phase through an intermediate form *E. exoptatus*.

Soergel[107] thought the ancestor, *E. planifrons* Falc. of the Pliocene of Asia and Europe,[108] e.g. in Bessarabia, Lower Austria, France and East Anglia[109] (Red Crag) and especially in Italy and North Africa (Algeria), gave rise to the Indian *E. hysudricus* and the European *E. meridionalis*. This evolved during the climatic changes into a temperate forest form, *E. antiquus*, and a periglacial steppe form, *E. trogontherii*. In the lower Pleistocene, there were transitions between *E. antiquus* and *E. trogontherii* and in middle Pleistocene more sharply defined end-forms, *E. antiquus*, *E. primigenius trogontherii*. The evolution he envisaged is as follows:

U. Pleistocene	*E. antiquus*	*E. primigenius*
		E. primigenius
M. Pleistocene	*E. antiquus*	*E. primigenius trogontherii*
		E. trogontherii primigenius
L. Pleistocene	*E. antiquus*	*E. trogontherii meridionalis*
Pliocene-Pleistocene transition	*E. meridionalis antiquus*	*E. meridinalis meridionalis*
U. Pliocene	*E. meridionalis primitivus*	

Blood analyses of the Berérovsk cadavre[110] show that the mammoth is more nearly related to the Indian than to the African elephant.

Depéret and Mayet,[111] who trace *E. meridionalis* from *E. planifrons* and *E. antiquus* from *E. ausonius* and place the origins of *E. africanus* and *E. indicus* in their respective continents, recognise a mammoth group of quite independent origin, consisting of (*a*) *Parelephas* (*E.*) *trogontherii* Pohl (= *E. intermedius* Jourdan[112] and *E. primigenius fraasi* Dietr.[113]), which began in the Villafranchian and had broader molars and thicker and fewer lamellae than (*b*) *E. primigenius* which originated in the Pliocene of San Paolo and (*c*) *E. sibericus* which first appeared in Europe in the Aurignacian of Gargas cave and differs from the preceding in its more numerous lamellae.

Osborn,[114] who derives all elephants from Africa, recognised the following Eurasiatic species of *Parelephas* in ascending progressive order: *P. trogontheriodes* Zuffardi, *P. trogontherii nestii* Pohlig, *P. trogontherii* Pohlig, *P. armeniacus* Falc., *P. intermedius* Jourdan, *P. wüsti* Pavlov, and the following succession of *Mammuthus*: *M. primigenius astensis* Dep. & May. of the upper Pliocene, *M. primigenius leith-adamsi*, *M. primigenius fraasi* Diet. and *M. primigenius primigenius* of the European Pleistocene which later evolved into the American *M. primigenius americanus* and *M. primigenius compressus*.

The meridional or southern elephant,[115] *Elephas meridionalis*, has wide and shallow molars with thick and smooth enamel and gigantic tusks. It lived in habitats of various kinds in Europe, west of the Rhine, and roamed into south France and Italy,[116] and as far as the Black Sea and North Africa.[117]

Elephas antiquus,[118] the ancient or straight-tusked elephant of Dawkins, known from skeletal parts, e.g. from Upnor, and from three prehistoric drawings,[119] viz. from Pindal Cave, North Spain, and Sud Oranais and Guébar-Rechim, Algeria, had narrow and deep teeth and tusks up to 5 m long. Adapted to grass-steppes, as according to Zeuner[120] the shape of its skull indicates, it lived in North Africa[121] and Phoenicia and the region south of the Alps and Pyrenees, e.g. the caverns on the Mediterranean shores[122] (Gibraltar, Malta, Italy, Sicily). It ranged as far north as Kirkdale and Settle in Yorkshire[123] and to Denmark,[124] Holland,[125] Antwerp, Berlin and Warsaw, and as far east as Bessarabia, Bucovina and the lower Danube (fig. 147). It was absent from Austria.

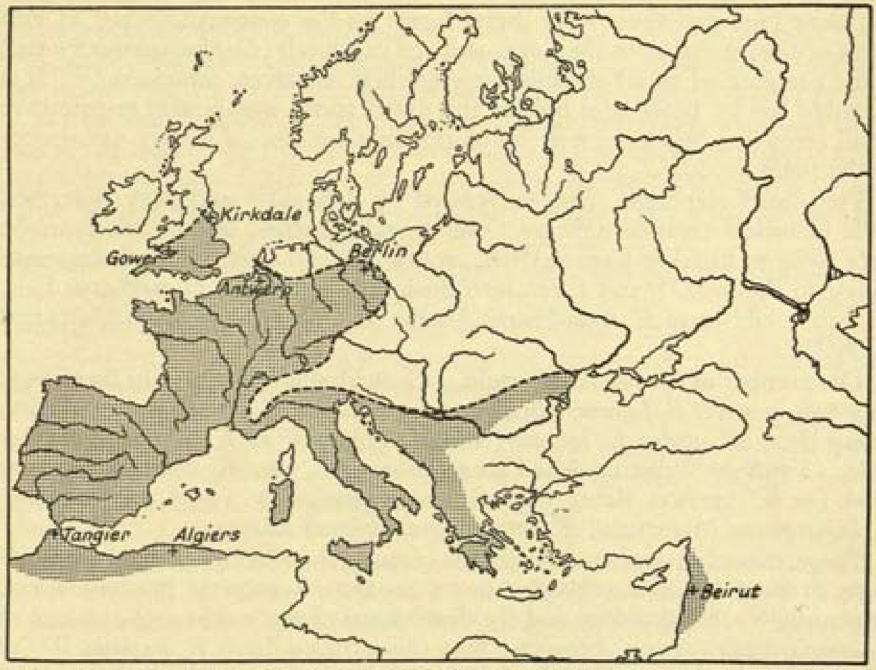

FIG. 147.—Map showing the distribution in Pleistocene Europe of *Elephas antiquus* (dash line = northern limit). M. Boule, *171*, fig. 21.

E. namadicus, the Asian equivalent of *E. antiquus*, ranged through Asia from Japan and China to India and Persia.[126]

E. trogotherii[127] Pohl includes all the specimens labelled *E. meridionalis* from the Cromer Forest Bed as well as some previously referred to *E. antiquus*. It was rare in France and was apparently wanting or rare in Italy, Spain and the Balkans.[128] The discovery of an entire skull in the Mosbach Sands with the typical teeth in place dispels all doubt of its specific difference.[129]

The first interglacial had elephants of the *meridionalis*, *antiquus* and *trogontherii* types; the second interglacial had *antiquus* and *trogontherii*, both readily distinguished but with intermediate variants; and the upper Pleistocene had *antiquus* and *primigenius*, each specifically quite distinct.

The succession of the American elephants[130] was *Mammuthus imperator* Leidy, *M. columbi* Falc. and *M. primigenius* Blum. Although other views

have been held,[131] in Soergel's opinion[132] *M. imperator* and *M. columbi* (Columbian mammoth) are as closely related as are *Elephas trogontherii meridionalis* and *E. trogontherii primigenius* in Europe and are descended from *E. meridionalis* Nesti, the *antiquus* branch in America being elided. Although the American mammoth may have been autochtonous, the last mutation of the *imperator-columbi* series, its origin is much more probably Eurasian[133]: it wandered into the Old World across Bering Strait.[134]

Dwarf elephants and hippopotamus. Confinement to the Mediterranean islands, following the breakdown of the land-bridges (see p. 1225), led to the evolution of a number of dwarf species of *Elephas* and *Hippopotamus* just as rhinoceros has become smaller since it was isolated in the East Indies. This deduction is denied[135] because Sicily was large enough to supply sufficient food and there were dwarf forms on the continent,[136] e.g. at Pisa and Corinth, in Spain, in the Volga area and in Algeria (*Elephas iolensis* Pomel) —the presence of dwarf elephants in Algeria is, however, contested.[137] It is disputed too by those who believe the dwarf forms immigrated as primitive small races (see below) or were small possibly because of certain deficiences in the plant food.[138]

The dwarf elephants, first recognised by Adams[139] and fully described with historical treatment[140] by Osborn and Vaufrey, include *E. cypriotes* Bate (0·85 m high) in Cyprus,[141] *E. creticus* Bate in Crete,[142] *E. lamarmorae* Major in Sardinia,[143] and *E. falconeri* Busk (*c.* 0·9 m high), *E. melitensis* Falc. (*c.* 1·40 m high) and *E. mnaidriensis* Adams (*c.* 1·90 m high) from Malta and Sicily.[144]

The number of species is uncertain. G. Schlesinger[145] thought there were only two, namely *E. falconeri* Busk and *E. melitensis*: O. Abel[146] preferred to group them all under *E. falconeri* and H. Pohlig[147] as *E.* (*antiquus*) *melitae* Falc. Vaufrey[148] distinguished three subspecies, viz. *E. antiquus falconeri* Busk (= *E. cypriotes* Bate), *E. antiquus melitensis* Falc. (= *E. creticus* Bate, *E. lamarmorae* Major) and *E. antiquus mnaidriensis* Adams.

These, the only representatives of the genus in the Mediterranean islands,[149] were deemed to have evolved from a separate branch of Pliocene dwarf elephants.[150] Morphology and the dimensions of the molars and cranium of *E. mnaidriensis* suggest, however, that this evolved from *E. antiquus*[151] (or *E. meridionalis antiquus*[152]), the biggest of all elephants, which roamed the Mediterranean lands before the islands were isolated. The degeneration, which affected the bones and much less the skull and teeth,[153] is borne out by the small size (the Upnor *E. antiquus* was almost 4 m high) and by the steady diminution of the animal as the remains are traced upwards through the beds; a cave near Palermo had two superimposed deposits with *E. melitensis* below and *E. falconeri* (*c.* 1 m high) above.[154] Osborn[155] however referred all the remains to the genus *Palaeoloxodon* and believed the dwarf elephants dated from the Würm glaciation, a considerable period after the disappearance of *Elephas antiquus*. He thought they sprang from some undiscovered genus of African elephants which also gave rise to the *E. namadicus* group of India and the Far East.

The dwarf hippopotamus of the Mediterranean includes the *Hippopotamus pentlandi* Falc. of Sicily[156] and *H. minutus* de Blainv. of Malta[157] and an intermediate form in Cyprus.[158] The islands have also yielded a dwarf fox[159] (*Vulpes vulgaris*) and a dwarf bear[160] (*Ursus arctos*).

Rhinoceros. The nomenclature and classification of the Pleistocene Rhinocerotidae[161] are somewhat confused. Five species have been distinguished: *Rhinoceros megarhinus* De Christol, *R. etruscus* Falc., *R. merckii* Jäg., *R. leptorhinus* Owen (= *R. hemitoechus* Falc.) and *R. antiquitatis* Blum (= *R. tichorhinus* Cuv.). Although some, including E. Wüst,[162] deem all five to be good species, other writers regard *etruscus* as identical with *megarhinus*,[163] with *hemitoechus*[164] or with *merckii*.[165] On the other hand, the *R. merckii* of continental geologists is equated with *R. megarhinus*[166] or with *R. leptorhinus* of English palaeontologists.[167] J. J. A. Bernsen[168] would include *R. megarhinus* and *R. hemitoechus* in *R. merckii* Jäg. This species, if it be distinct, was most probably, as the Mauer intermediate fauna shows, descended from *R. etruscus*,[169] though its occurrence in the Cromer Forest Bed may point to a separate origin.[170]

Less certain are the *R. hundsheimensis* of F. Toula[171] (= *R. etruscus* Falc. race *hundsheimensis* Toula according to Freudenberg[172]) and the *R.* (*merckii*) *mosbachensis* of H. Pohlig[173] who placed the latter intermediate between *R. merckii* and *R. etruscus*. The Pleistocene Rhinocerotidae, which are in all probability relatives of the nearly extinct white or square-nosed rhinoceros,[174] *Ceratotherium simus* of Africa, may be classified as *Dicerorhinus etruscus*, *Diceros megarhinus*, *D. leptorhinus* (= *Rhinoceros hemitoechus* Falc. = *R. merckii* Jäg.) and *Tichorhinus antiquitatis* Blum (= *R. tichorhinus* Cuv.).

Diceros etruscus, as Dawkins and Falconer described it,[175] was small. Its upper true molars are distinctive; for they had low crowns, abruptly tapering colles, and a stout cingulum in the exterior aspect. The septum shows the beginning of the ossification which continued in late forms and attained its maximum in *Tichorhinus antiquitatis*.

Diceros megarhinus[176] ("large-nosed" rhinoceros) was of slender build, had two horns with largely developed nasals, and lacked a cloison or bony partition between the nostrils. Like *etruscus* it lived in south Europe during the Pliocene as well as in the Cromer Forest Bed.

D. leptorhinus Owen (= *R. merckii* of continental writers), the leptorhine or narrow-nosed rhinoceros, was a slender-limbed bicorn species with a partially ossified septum. Its descent was possibly from *Dicerorhinus etruscus*,[177] either the Pleistocene or the Pliocene form.[178] It was widely distributed in central Europe (fig. 148) and as far north as Graudenz and Menthen in north Germany[179] and Grünenthal in Schleswig-Holstein,[180] and wandered westwards into Denmark[181] (= *D. kirchbergensis*), into the British Isles (South Wales, Thames valley, and through the eastern counties to Market Weighton, Yorkshire). It was absent from north Siberia though it occurred in the Altai caves. *Ceratotherium simus*[182] replaced it on the Atlantic slope of Morocco.

A distinct generic type allied to rhinoceros was the *Elasmotherium sibericum*[183] of Pleistocene Siberia, Russia and the Rhine region.

Machairodus. The Pliocene had two species of *Machairodus*, namely, *M. crenatidens* Weith. of, for example, Val d'Arno,[184] and *M. cultidens* Cuv. whose osteology S. Schaub[185] for the first time fully described from an almost complete skeleton from Senèze (Haute-Loire) and complementary parts from Val d'Arno. The Pleistocene *M. latidens* Owen, the European sabre-tooth tiger,[186] was descended from *M. crenatidens*[187] yet differed from it, among other ways, in the possession of smaller canine teeth.

M. latidens is relatively rare; it occurs in Val d'Arno, Auvergne,[188] in the Pleistocene caves of Lower Austria and Moravia[189] (J. N. Woldřich[190] has

described a species, *M. moravicus* from this area), at Mauer and a few other places in Germany,[191] in the bottom bed at Abbeville,[192] and occasionally in England[193] (Kent's Cavern, Oreston, Creswell and Cromer Forest Bed). *Machairodus* survived into the lower Pleistocene in China and Korea.[194]

Cave lion. *Machairodus* was replaced by other large Felidae. The cave lion, considered by Goldfuss and Owen to be specifically distinct from *Felis leo*,[195] was later regarded as a variety of the existing lion,[196] as a northern race or races of the recent lion of Africa and west Asia,[197] or as an extinct lateral

FIG. 148.—Map showing the distribution in Pleistocene Europe of *Diceros merckii* (dash line = northern limit). M. Boule, *171*, fig. 23.

branch descended from the great cats (*F. arvernensis*) of the Pliocene of France and Italy.[198] Some maintain that the remains were more probably those of a tiger,[199] that they were distinct from both lion and tiger,[200] or that two types are recognisable, one with affinities with lion, the other with tiger.[201]

The cave lion was characterised by large size (it was one-third or even one-half bigger than the modern lion), a feature it shared with the cave hyaena and cave bear, the Pleistocene jaguar of the Patagonian caves,[202] the Pleistocene panther,[203] the Giant Deer (height, 10 ft or *c.* 3 m; antler spread, 12 ft or 3·5 m), the glutton, marmot, puma and jaguar of North America,[204] the South American rodents, Bovids in the Pyrenees, giant beavers in both Europe and North America, giant kangaroos and wombat-like forms in Australia, Madagascar lemurs and the tiger of the cold Altai Mountains, Lena valley, and the country bordering the perpetual snows in the Himalayas.[205] Like this tiger, it was apparently not very sensitive to cold; it ranged upwards into the caves of Wildkirchli (1477 m) and Wildenmannisloch (1628 m) and was widely distributed in Europe during the cold Mousterian and Magda-

lenian. This tendency of many Pleistocene animals to grow to large size may be a sign that, on account of the cooling which retarded sexual development, the conditions approximated to a kind of optimum.[206] Mammals and birds and some invertebrates in cooler climates are, in accord with Bergmann's rule[207] (1847), to-day larger in body size than the same species in warm climates, and a similar change (probably concerned with the temperature regulation of the animal) can be experimentally induced by environmental stimuli.[208]

M. Boule[209] has fully discussed the cave lion's osteology and distribution. Occurring in far smaller numbers than the cave bear, it has been traced from England (e.g. Kirkby Moorside and especially in the Mendips) across Europe to Mark Brandenburg,[210] Austria, Hungary, Odessa, Ural Mountains and Volga region (except at Kiev, it is outside the erratic limit of Russia[211]) and southwards through France into Spain, North Africa and Phoenicia.[212]

Other Pleistocene species of *Felis* are the panther, *F. pardus* L. which occurs for example in several English localities[213] (e.g. Barnwell, Bleadon, Sandford Hill) and was widespread over Europe[214] to Italy in the south and Hungary and Transylvania in the north-east—the remains in the Altai belong most probably to *F. uncia* which still lives here; the lynx,[215] *F. lynx* L., which is found in many caves in the British Isles from Somerset to Yorkshire, Inchnadamph and Kilgreany, and over Belgium and Germany and as far south as Côte d'Azur, Italy, Spain and Portugal; and a small lion, *F. nobilis* Gray, of south Bohemia.[216]

Cave hyaena. The commonest Pleistocene hyaena was, according to Abel,[217] *Hyaena striata* which lived in early Pleistocene time from west Germany to England and France and later in south Europe and west Asia. K. Ehrenberg,[218] after comparing all available material, concluded that the cave hyaena was the most specialised form and should be given specific distinction as *H. spelaea* Goldf.

The cave hyaena, like the cave lion, was because of its size considered to be an extinct species by the early naturalists, including Goldfuss. Later, following the lead of Dawkins,[219] it was regarded[220] as a northern variety of the existing spotted hyaena, *Crocuta* (*Hyaena*) *crocuta*, of Africa south of the Sahara. Boule[221] distinguished four Pleistocene species: *H. spelaea*, descended from *H. intermedia* (= a variety of *H. spelaea* in E. Harlé's opinion[222]), *H. brunnea*, and *H. striata*. Others[223] recognise also *H. brevirostris* Aymard, a descendant of *H. robusta*.

The cave hyaena's descent is obscure, though the absence of the family from North America proves it to belong to the Old World—true hyaenas are known from the lower Pliocene of Greece, Samos, Persia and India. According to R. Lydekker,[224] the ancestor of *H. crocuta* inhabited India during the Pliocene (Siwalik Hills) and Pleistocene and *H. crocuta* itself lived there during the Pleistocene, e.g. in the Karnul caves, Madras, as well as in central Asia and China, and spread westwards into Syria, Palestine and North Africa where it has been discovered in Algerian caves. *H. crocuta*, therefore, was an Asian and not an African animal. The jaws at Grays in Essex have been said to resemble the Pliocene ancestor more closely than do the later varieties.[225] Boule[226] on the other hand traced the cave hyaena to the Pliocene *H. perreiri* through *H. intermedia*. The hyaenas of the crocuta group became larger during the Pleistocene; the contemporaries of the warm rhinoceros were smaller than those of later times.[227]

Cave hyaena roamed from the Altai and China to Gibraltar, Belgium, England, Odessa and Palestine[228]; with the cave bear to Monaco,[229] Tuscany[230] and Bergamo and the Crimea[231]; and with the cave lion as far north in Europe as Thiede[232] (N. Harz).

Cave bear. The Pleistocene bears[233] were very variable—the phylogeny of the Tertiary bears,[234] of which the earliest (*Ursavus*) appeared in the Neogene of Württemberg,[235] is outside the scope of this work. During the Pleistocene, some of the bears evolved into a form resembling the present North American grizzly (*Ursus horribilis*), and others became the European brown bear (*U. arctos*) which was directly descended from the Pliocene *U. arvernensis* or *U. etruscus*[236] and though known from the early and middle Pleistocene only became abundant in Magdalenian time.[237] Others again by reducing the anterior pre-molars and shortening the tibia and fibula and greatly elongating other bones developed into the cave bear, *U. spelaeus*, the evolution probably taking place at different times in different places. The fossil bears probably constitute a graded series[238]—the young cave bear at birth was scarcely bigger than the young brown bear[239] and adult cave bears, as the many specific names given them testify, varied in size among themselves by about one-third[240]—H. C. Harrison[241] distinguished 86 species and subspecies among the brown and grey bears of Pleistocene North America. In the unfavourable conditions of late-Pleistocene time the cave bear diminished in size[242] (Drachenhöhle, Drachenloch, Wildenmannisloch, Wildkirchli and Mixnitz).

The cave bear, which has been reconstructed several times,[243] is generally deemed to have evolved from the Pliocene *U. arvernensis* Croizet, a forest bear closely related to the small *U. etruscus*, through a stage of *U. deningeri* Reichenau[244] (which in Soergel's opinion was a steppe bear[245]) and a stage of *U. suessenbornensis*.[246] This form and the many others which have been distinguished, e.g. *U. savini*, *U. arctoides*, *U. giganteus* and *U. planus*, may have been intermediate between *U. arctos* and *U. spelaeus*.[247] L. Rüger[248] thought the *etruscus-arvernensis* forms were possibly a lateral branch. S. Maier[249] has fully discussed the evolution of the European bears and S. H. Reynolds,[250] who monographed the British Pleistocene bears, follows earlier writers[251] in recognising the specific distinction of *U. spelaeus* and groups all other British remains as *U. arctos*. Ehrenberg[252] discussed the ontogenetic development and denied that the measurements and indices which Soergel[253] worked out can be used for specific determination.

The cave bear, far more plentiful than the Pleistocene lion, was distributed in caves over Europe south of the ice-sheet[254] from England to Odessa and north Caucasus (there is none in Siberia) and as far south as central Spain, southern Italy, the Mediterranean coast at Monaco[255] and even Algeria. Its range exceeded that of any other Pleistocene animal. Though its mode of life caused it to be extremely rare in the open country of the wide valleys and lowlands,[256] it spread from the German Mittelgebirge at 200 m and the foot of the Alps through an altitude exceeding 2000 m,[257] ascending for example to Drachenhöhle (1000 m), Schnurenloch (1220 m), Wildkirchli (1477 m), Wildenmannisloch (1628 m), la grotte des Dentaux (1680 m), Furgelfirst (1700 m), Kilchli (1810 m), Ranggiloch (1845 m), Schreiberwandhöhle (2200 m), Steigelfadbahn (960 m) and Drachenloch (2445 m). Its caves were favoured topographically,[258] i.e. in temperature conditions, dryness, freedom from falling stones, springs in the neighbourhood, rising floors and

roominess. The associated animals were zonally arranged[259]: above 1600 m, there occurred chamois, ibex, and marmot with reindeer; somewhat lower and below 700 m there lived horse, reindeer and woolly rhinoceros; and at still lower levels there was Merck's rhinoceros.

The Pleistocene bears of central Europe belong apparently to *U. arctos*[260] whose range then embraced the Urals, Altai and China.

The Pleistocene bears of North America,[261] *U. americanus*, *U. amplidens* and *U. horribilis*, wandered from Eurasia where the bears first appeared in the Miocene—Tertiary bears are unknown in North America.

Beavers. The Pleistocene beavers belonged to the still living *Castor fiber* and the extinct *Trogontherium cuvieri*[262] Fischer, a big beaver distinguished by the nature of the enamel folds of its molars. It first appeared in the Pliocene of Val d'Arno and St. Prest and continued into the interglacial beds of Cromer, the Thames terraces, and of Mosbach, Taubach, Mauer and Süssenborn. Other species, such as the *Conodontes* [*Trogontherium*] *boisvilleti* Laugel (said by A. Schreuder[263] to be the beaver of Tegel and of France and England), and *T. soergeli* Rüger,[264] are of uncertain value.

The Pleistocene beavers were widely distributed south of the ice-sheet[265]—the beaver (*Castor fiber*) of north Germany, Denmark, Scandinavia and the Baltic provinces of Russia within this region, immigrated postglacially about Ancylus time. They occurred in the eastern part of East Anglia and at Greenhithe in Kent, as mapped by Schreuder,[266] and on the continent of Europe in the basins of the Sâone, Seine, Meuse (Tegelen) and Rhine (Mosbach, Jochgrim, Mauer, Hochsachsen), in central Bohemia and on the north coast of the Sea of Azov.[267]

Bovids. The Pleistocene Bovids[268] of Europe are *Bison priscus* and the aurochs, *Bos primigenius*. Both were widespread. Bison was more abundant and was closely related to the upper Pliocene *Leptobos*[269] (see p. 820). Many zoologists and palaeontologists recognise a large steppe bison, *Bison priscus*, with slightly out-turned horns, and a woodland bison, *B. europaeus* Owen (= *B. bonasus* L.), with shorter and more curved horns, which descended from an earlier form *B. schoetensachi*. *Bison priscus* died out in the Pleistocene[270] but *B. europaeus* continued into Recent time.

(*b*) *Steppe Mammalia*

Numerous animals, characteristic of or confined to the present steppes of Russia and Siberia, had a wider range during the Ice Age; they included the jerboa (*Allactaga jaculus*), red suslik (*Citellus rufescens*), fawn-coloured suslik (*C. fulvus*), bobac (*Marmota bobak*), tailless hare or pika (*Ochotona pusillus*), hamster (*Cricetus vulgaris*), saïga antelope (*Antelope saiga*, *Saïga tatarica*), steppe elk (*Alce latifrons*), cuon (*Cuon alpinus* var. *europaeus*), horses, e.g. *Equus hemionus* and a number of voles (*Arvicola*)—the latter, by their gradual evolution, are among the most useful leading fossils for the Pleistocene.[271] Nehring[272] has fully described the characters and distribution of the steppes and the steppe animals of both the present and the past.

Horse. Pleistocene Europe had a number of wild horses which differed in their size, appearance and skulls as well as in their distribution. They have been the subject of numerous publications.[273] Dawkins[274] emphasised Cuvier's view[275] that they were specifically indistinguishable from *Equus caballus* of to-day. This was descended from *E. stenonis* Cocchi (= *E. fossilis*

Cave hyaena roamed from the Altai and China to Gibraltar, Belgium, England, Odessa and Palestine[228]; with the cave bear to Monaco,[229] Tuscany[230] and Bergamo and the Crimea[231]; and with the cave lion as far north in Europe as Thiede[232] (N. Harz).

Cave bear. The Pleistocene bears[233] were very variable—the phylogeny of the Tertiary bears,[234] of which the earliest (*Ursavus*) appeared in the Neogene of Württemberg,[235] is outside the scope of this work. During the Pleistocene, some of the bears evolved into a form resembling the present North American grizzly (*Ursus horribilis*), and others became the European brown bear (*U. arctos*) which was directly descended from the Pliocene *U. arvernensis* or *U. etruscus*[236] and though known from the early and middle Pleistocene only became abundant in Magdalenian time.[237] Others again by reducing the anterior pre-molars and shortening the tibia and fibula and greatly elongating other bones developed into the cave bear, *U. spelaeus*, the evolution probably taking place at different times in different places. The fossil bears probably constitute a graded series[238]—the young cave bear at birth was scarcely bigger than the young brown bear[239] and adult cave bears, as the many specific names given them testify, varied in size among themselves by about one-third[240]—H. C. Harrison[241] distinguished 86 species and subspecies among the brown and grey bears of Pleistocene North America. In the unfavourable conditions of late-Pleistocene time the cave bear diminished in size[242] (Drachenhöhle, Drachenloch, Wildenmannisloch, Wildkirchli and Mixnitz).

The cave bear, which has been reconstructed several times,[243] is generally deemed to have evolved from the Pliocene *U. arvernensis* Croizet, a forest bear closely related to the small *U. etruscus*, through a stage of *U. deningeri* Reichenau[244] (which in Soergel's opinion was a steppe bear[245]) and a stage of *U. suessenbornensis*.[246] This form and the many others which have been distinguished, e.g. *U. savini*, *U. arctoides*, *U. giganteus* and *U. planus*, may have been intermediate between *U. arctos* and *U. spelaeus*.[247] L. Rüger[248] thought the *etruscus-arvernensis* forms were possibly a lateral branch. S. Maier[249] has fully discussed the evolution of the European bears and S. H. Reynolds,[250] who monographed the British Pleistocene bears, follows earlier writers[251] in recognising the specific distinction of *U. spelaeus* and groups all other British remains as *U. arctos*. Ehrenberg[252] discussed the ontogenetic development and denied that the measurements and indices which Soergel[253] worked out can be used for specific determination.

The cave bear, far more plentiful than the Pleistocene lion, was distributed in caves over Europe south of the ice-sheet[254] from England to Odessa and north Caucasus (there is none in Siberia) and as far south as central Spain, southern Italy, the Mediterranean coast at Monaco[255] and even Algeria. Its range exceeded that of any other Pleistocene animal. Though its mode of life caused it to be extremely rare in the open country of the wide valleys and lowlands,[256] it spread from the German Mittelgebirge at 200 m and the foot of the Alps through an altitude exceeding 2000 m,[257] ascending for example to Drachenhöhle (1000 m), Schnurenloch (1220 m), Wildkirchli (1477 m), Wildenmannisloch (1628 m), la grotte des Dentaux (1680 m), Furgelfirst (1700 m), Kilchli (1810 m), Ranggiloch (1845 m), Schreiberwandhöhle (2200 m), Steigelfadbahn (960 m) and Drachenloch (2445 m). Its caves were favoured topographically,[258] i.e. in temperature conditions, dryness, freedom from falling stones, springs in the neighbourhood, rising floors and

roominess. The associated animals were zonally arranged[259]: above 1600 m, there occurred chamois, ibex, and marmot with reindeer; somewhat lower and below 700 m there lived horse, reindeer and woolly rhinoceros; and at still lower levels there was Merck's rhinoceros.

The Pleistocene bears of central Europe belong apparently to *U. arctos*[260] whose range then embraced the Urals, Altai and China.

The Pleistocene bears of North America,[261] *U. americanus, U. amplidens* and *U. horribilis*, wandered from Eurasia where the bears first appeared in the Miocene—Tertiary bears are unknown in North America.

Beavers. The Pleistocene beavers belonged to the still living *Castor fiber* and the extinct *Trogontherium cuvieri*[262] Fischer, a big beaver distinguished by the nature of the enamel folds of its molars. It first appeared in the Pliocene of Val d'Arno and St. Prest and continued into the interglacial beds of Cromer, the Thames terraces, and of Mosbach, Taubach, Mauer and Süssenborn. Other species, such as the *Conodontes* [*Trogontherium*] *boisvilleti* Laugel (said by A. Schreuder[263] to be the beaver of Tegel and of France and England), and *T. soergeli* Rüger,[264] are of uncertain value.

The Pleistocene beavers were widely distributed south of the ice-sheet[265]—the beaver (*Castor fiber*) of north Germany, Denmark, Scandinavia and the Baltic provinces of Russia within this region, immigrated postglacially about Ancylus time. They occurred in the eastern part of East Anglia and at Greenhithe in Kent, as mapped by Schreuder,[266] and on the continent of Europe in the basins of the Saône, Seine, Meuse (Tegelen) and Rhine (Mosbach, Jochgrim, Mauer, Hochsachsen), in central Bohemia and on the north coast of the Sea of Azov.[267]

Bovids. The Pleistocene Bovids[268] of Europe are *Bison priscus* and the aurochs, *Bos primigenius*. Both were widespread. Bison was more abundant and was closely related to the upper Pliocene *Leptobos*[269] (see p. 820). Many zoologists and palaeontologists recognise a large steppe bison, *Bison priscus*, with slightly out-turned horns, and a woodland bison, *B. europaeus* Owen (= *B. bonasus* L.), with shorter and more curved horns, which descended from an earlier form *B. schoetensachi*. *Bison priscus* died out in the Pleistocene[270] but *B. europaeus* continued into Recent time.

(*b*) *Steppe Mammalia*

Numerous animals, characteristic of or confined to the present steppes of Russia and Siberia, had a wider range during the Ice Age; they included the jerboa (*Allactaga jaculus*), red suslik (*Citellus rufescens*), fawn-coloured suslik (*C. fulvus*), bobac (*Marmota bobak*), tailless hare or pika (*Ochotona pusillus*), hamster (*Cricetus vulgaris*), saïga antelope (*Antelope saiga, Saïga-tatarica*), steppe elk (*Alce latifrons*), cuon (*Cuon alpinus* var. *europaeus*), horses, e.g. *Equus hemionus* and a number of voles (*Arvicola*)—the latter, by their gradual evolution, are among the most useful leading fossils for the Pleistocene.[271] Nehring[272] has fully described the characters and distribution of the steppes and the steppe animals of both the present and the past.

Horse. Pleistocene Europe had a number of wild horses which differed in their size, appearance and skulls as well as in their distribution. They have been the subject of numerous publications.[273] Dawkins[274] emphasised Cuvier's view[275] that they were specifically indistinguishable from *Equus caballus* of to-day. This was descended from *E. stenonis* Cocchi (= *E. fossilis*

Owen), a species (probably a developmental series[276]) widely distributed over Pliocene Europe and North Africa, through transition forms such as *E. robustus* of the Auvergne[277] and others in the Cromer Forest Bed, at Solilhac and at Süssenborn; it had become the present-day horse in the Chellean beds of North France,[278] Nevertheless, several Pleistocene species have been created (cf. Boule's list[279]) which rest on insufficient fossil evidence and ignore the wide variations shown by modern horses. O. Antonius,[280] for example, recognised (*a*) *E. przewalski* Pol. (= *E. ferus*, Pall), a wild Asian horse, the Solutrean horse; *E. germanicus*, Nehr.; *E. woldřichi* Ant.; (*b*) *E. gmelini* Ant.; (*c*) *E. abeli* Ant. evolved from *E. süssenbornensis*, apparently the last European member of the *E. robustus* lineage. W. v. Reichenau[281] distinguished five subgenera: (*a*) the zebra horses, *Hippotragus* with *E. stenonis*, *H. süssenbornensis* (intermediate between *E. stenonis* and *E. germanicus*) and *H. altidens*; (*b*) *Eohippus*, e.g. *E. steinheimensis*; (*c*) *Equus* s. str. e.g. *E. mosbachensis*, *E. taubachensis*, *E. germanicus*; (*d*) *Microhippus*, e.g. *Przewalski fossilis*; and (*e*) *Asinus*—the Pleistocene asses of Europe have been separately monographed[282]: *E.* (*Asinus*) *hydruntinus* occurred at Val d'Arno and spread in Pleistocene time over most of west Europe.[283]

E. Schwarz[284] divided the Pleistocene horses, according to their size, into: (*a*) *E. caballus caballus*, a small upper Pleistocene (Aurignacian, Solutrean and Magdalenian) to Recent form (= *E. caballus celticus* Ewart; *E. robustus* Ewart; *E. gracilis* Ewart—the "species" are probably varieties adapted to food supply and environment); (*b*) *E. caballus placidens* Owen of the middle Pleistocene (= *E. fossilis minor* Woldř.; *E. taubachensis* Freud.; *E. woldřichi* Ant.; *E. steinheimensis* Reich.); (*c*) *E. caballus robustus* Pomel, a large Pliocene form from Red Crag and Cromer Forest Bed (= *E. süssenbornensis*, *E. mosbachensis*, Reich., *E. altidens* Reich.); and (*d*) *E. caballus przewalski* Pol. An *E. transilvanicus* has been distinguished in Rumania.[285] Several types were identified from cave drawings.[286]

The main centre of dispersal of the horse has been North America. Thence they wandered into Europe over Asia and into South America which had several Pleistocene species.[287]

Europe had no Pleistocene zebra: the identification of certain Magdalenian paintings with this animal is apparently erroneous.[288] A perfectly preserved skull at Steinheim an der Murr in Württemberg proves for the first time the existence of a buffalo (*Buffelus murrensis*) in Pleistocene Europe.[289]

Other animals. The mammoth and woolly rhinoceros (see below) have been claimed as denizens of the steppes.[290] H. Hilzheimer[291] concluded from the nature of the food found in the Galician carcases of *Tichorhinus antiquitatis* and the build of its mouth that this animal lived in swamp woods or parklands. The food remains in a tooth in the Eem beds of the Kiel Canal led to an expression of this view for *Diceros leptorhinus*.[292]

Among the Canidae,[293] the oldest Pleistocene form is *Canis neschersensis* of Mosbach and Mauer and of the upper Pliocene of France. Of the same age or even older are *Canis lupus* and *Vulpes vulpes*, e.g. in the Red Crag of England and the St. Prestian of France. In central Europe the earliest appearances were later, viz. the Taubach travertine and the middle Palaeolithic of Krapina.

Pleistocene range. The Russian and Siberian steppe animals ranged over most of Asia and into Europe[294] (see pp. 527, 1436). The Saiga ante-

lope, for example, now restricted in Asia to south of 52° N., spread as far as 73° N.[295] and even into Alaska.[296] It has occasionally been discovered in Germany, Poland, Bohemia, Hungary, Belgium, England[297] (Twickenham and Langwith Cave), Denmark,[298] and more plentifully in south-west France,[299] e.g. in the Dordogne and sub-Pyrenees. *Ochotona pusillus* roamed into Germany,[300] into Moravia, Hungary and Poland[301] and into the Magdalenian caves of the Dordogne.[302] *Cuon alpinus*, var. *europaeus*, the wild dog now confined to central and eastern Asia—other species are *C. dubuis stehleni*, *C. priscus*, *C. alpinus*—spread into Moravia and to Cotencher, Ariège, Sardinia, north Spain, Monaco and Italy.[303] The latter had a number of steppe birds though the climate generally was that of present Britanny[304] (cf. p. 655).

(*c*) *Tundra Mammalia*

The distinction between tundra and steppe animals is not always easy to maintain. Osborn's[305] Eurasian group, for example, comprised animals with hypsodont teeth, of temperate meadows, e.g. Bison, urus, shrew, hamster and field vole, and forest animals with brachydont teeth, e.g. *Cervus*, *Sus scrofa*, *Cervus capreolus*, *Alce latifrons*, *Felis catus*, etc., and the extinct *Megaceros giganteus*, *Ursus spelaeus* and *Trogontherium*. Nevertheless it is agreed that the tundra claimed the still-living *Rangifer tarandus*, *Ovibos moschatus*, *Gulo luscus*, *Alopex lagopus*, *Lepus variabilis*, *Microtus nivalis*, *M. ratticeps*, *Dicrostonyx torquatus*, *Lemmus lemmus*, *Mustela*, and the extinct *Elephas primigenius*, *Tichorhinus antiquitatis* and, possibly, *Megaceros giganteus*.

Reindeer. The reindeer,[306] which lives on grass and willow shoots in summer and on lichens and moss in winter, is dispersed to-day from the northern edge of the temperate forest (Sweden, 62° N.; Norway, 60° N.; Russia, 56° N.) to the Arctic Ocean in Europe and America[307] and to Greenland and Spitsbergen.[308] Since it varies widely in size, colour, antler shape, etc., different "races" or "species" have been established. A. Jacobi[309] recognised *Rangifer tarandus* of Eurasia and *R. arcticus* of North America. R. Lydekker,[310] basing his conclusions upon the antlers, distinguished no less than six races; a Scandinavian *Cervus tarandus*, a Spitsbergen *C. tarandus spitsbergensis* (this is a dwarfed form on the outer limits of the habitat[311]), a Newfoundland *C. tarandus terrae novae*, a Greenland *C. tarandus groenlandicus*, the caribou *C. tarandus arcticus* and the woodland caribou, *C. tarandus caribou*. These are all specifically identical with *C. tarandus*[312] as are, according to T. Kormos,[313] the species *Rangifer granti*, *R. pearyi* and *R. osborni* created by Allen[314] who also distinguished a further species *R. stonei* in the Kenai Peninsula of Alaska.[315] A new species, *R. constantini*, has also been created.[316] Most writers agree in recognising a "barren ground" or tundra group in which the antlers are large, rounded and slender and the beam and tines are only slightly palmated, and a "woodland" group with comparatively small horns, thicker and flatter, the beam and tines being more palmated (fig. 149).

The reindeer of the Pleistocene was the tundra and not the forest form, as E. Lartet, A. Gaudry and M. Boule showed for France,[317] W. Dames, F. Wahnschaffe, A. Jentzsch and K. Gripp for north Germany[318] and M. Degerbøl for Denmark.[319] Scharff,[320] who used cranial character for diagnosis, thought most European reindeer belonged to the Siberian form

and that the American types were mainly represented in Scandinavia and Ireland. The reindeer of the Pre-boreal Meiendorf (see p. 880) was apparently *R. arcticus*.[321]

The reindeer's immediate ancestor is unknown since the earliest remains are indistinguishable from the present forms.

The reindeer roamed widely and in enormous numbers during the Pleistocene.[322] It ranged from Scania[323]—only three have been noted from central Scandinavia (Tennult, Edared and island of Öland)—southwards to Garonne[324] and Santander and the Picos de Europa in Spain,[325] to Bayonne, Narbonne and the Mediterranean coast[326] at Grimaldi and Monaco (Aurignacian) and to central Italy, becoming rare in Galicia[327] but spreading through the Moravian Gate to Moravia[328] and the neighbourhood of Trieste and of Laibach, to the northern bank of the Danube and into Transylvania, over Russia to the Black Sea and Sea of Azov and to 57° N. in Siberia[329]—it did not reach China.

In North America,[330] it extended in places to the 42nd parallel (fig. 150).

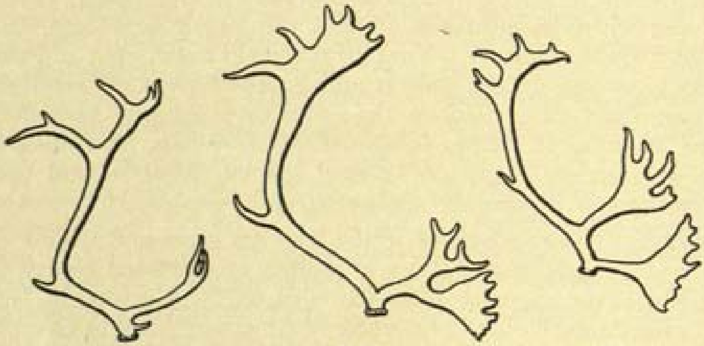

FIG. 149.—Reindeer antlers. (*a*) *Rangifer tarandus* L., (*b*) *Rangifer arcticus osborni* Allen, (*c*) *Rangifer caribou* Gm. O. Tschumi, *1918*, p. 247, fig. 107.

Alce malchis, the Moose Deer of Canada, and the Elk of Norway, had no representatives in Pleistocene Britain.[331] *Cervus elephas* had a wide distribution.[332]

Musk ox. The ontogenic and other varieties of the living musk ox or sheep have been described by Allen[333] who thought the musk ox, *Ovibos wardi*, of Ellesmere Land, Grinnell Land and Greenland was specifically distinct from the *O. moschatus* of the mainland that formerly roamed westwards into Alaska.[334] With Jakobi,[335] he assigned the Eurasian remains to *O. pallantis* Smith.

R. Kowarzik, who has studied the living musk ox,[336] referred the fossils on the basis of their skulls[337] to a western group, *O. moschatus mackenzianus* Kow. which evolved after maximum glaciation from an eastern group, *O. fossilis*. While the former retreated over Europe, Russia and the Bering Strait into North America, the other became rare and extinct (= *O. priscus* Rütimeyer and of W. Staudinger[338]). It was restricted to four instances only, viz. Cromer Forest Bed, Upper Silesia, Cracow and Frankenhausen. Kowarzik's conclusions, however, are apparently unjustified; his diagnostic criteria are minor osteological characters and sex differences.[339] J. Andrée[340]

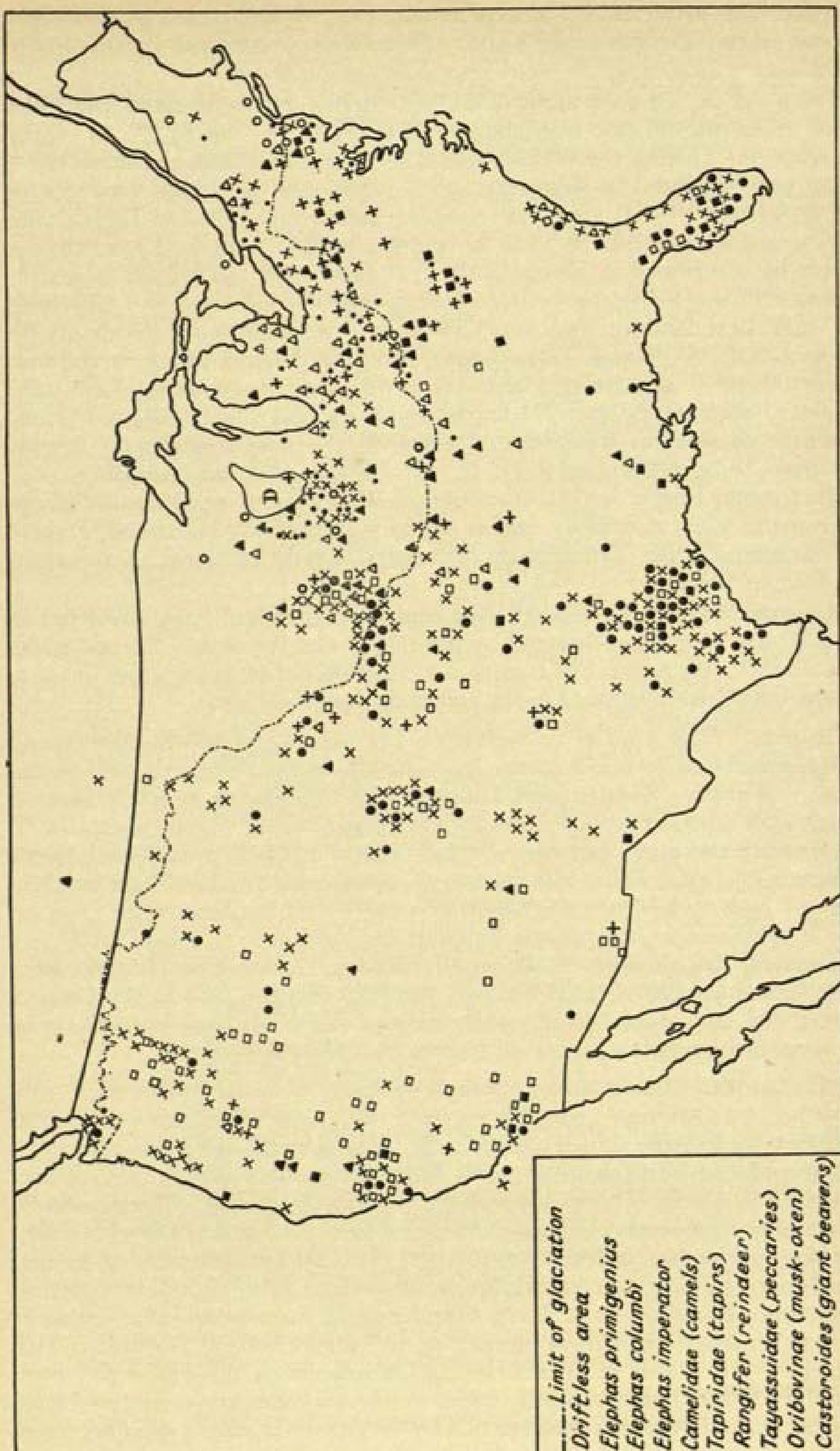

FIG. 150.—Range of reindeer, arctic fox, mammoth and other animals in the United States during Pleistocene time. O. P. Hay, *717, 718, 719* (redrawn from several plates).

assigned both living and Pleistocene musk ox to two subspecies, *O. moschatus moschatus* and *O. moschatus wardi*. *Praeovibos* is confined to the lower Pleistocene (see p. 819): Tertiary ancestors are unknown.

The musk ox, the most arctic of all living herbivores, is found in Ellesmere Land, in north and east Greenland, and between 60° and 83° N. in North America.[341] During the Glacial period its distribution was circumpolar.[342] It not only migrated to Kentucky and Virginia and the middle latitudes in North America[343] (fig. 150)—one complete carcase was found in Eschscholtz Bay—but it lived in Siberia[344] as far south as 57° 47′ N. in the Lena valley—it may have survived in Mongolia up to *c.* 2000 years ago.[345] It ranged in Europe[346] from Schleswig-Holstein and Königswusterhausen and Oderberg in Mark Brandenburg and West Prussia[347] through south Germany,[348] Upper Silesia,[349] Poland, Transylvania, Moravia, Austria, Hungary and east Karawanken,[350] the Swiss Plain (cf. list[351]) and Jugoslavia.[352] It also expanded through Belgium[353] to the Pyrenees and the Dordogne[354] (occasionally depicted in palaeolithic carvings[355]), the most southerly occurrence in Europe being at Périgord in 45° N. In England,[356] it has been discovered in the Cromer Forest Bed, at Maidenhead—the first European locality where the remains were identified—and at Bromley, Freshford, Barnwood, Fisherton, Crayford, Erith, Trimingham, Frampton, Leeds, Ightham, as well as on the Dogger Bank.

Kowarzik's list of 81 localities for central Europe and Asia, compiled in 1912,[357] has been supplemented by himself[358] and for central Europe by E. Stromer.[359] W. Soergel[360] compiled a complete list of 95 localities in 1942, of which 85% were situated in the glacial or periglacial zone.

Glutton. The glutton or wolverine lives to-day in North America in regions inhabited by reindeer, musk ox and elk, in North Siberia, and on the fjeld of Norway, Sweden and Lapland. During glacial times it roamed widely over central Europe[361] into Poland, Transylvania[362] and Jugoslavia,[363] to Denmark and north Germany,[364] and as far south as Grimaldi and Ariège in France[365] (palaeolithic man portrayed it in the cave of Lorthet, Pyrenees) and to Kesslerloch[366] and the Ligurian coast.[367] It wandered with musk ox into Italy[368] and westwards into Belgium and the Cromer Forest Bed[369] and into several British caves[370] (Barnwell, Bleadon, Gower, Plas Heaton, Creswell, Kent's Cavern). T. Kormos[371] has held that the *Gulo* in the Cromer Forest Bed and other "preglacial" localities could not have been the cold *G. luscus* but a separate, ancestral species *G. schlosseri*, n. sp.

Mammoth. The mammoth, whose history and development were fully described by Osborn,[372] was named from the Tartar *Mamantu* or "ground dweller" because the animal occurs in the frozen ground of Siberia; the name was introduced into scientific use as *Mammut* by Blumenbach in 1799 and gallicised by Cuvier[373] into *Mammouth*. It was also termed *Mammonteus*[374] (preferably *Mammuthus*[375]), or, because of its curved tusks, *Dicyclotherium*, the beast of the two circles[376] (cf. p. 617). It is the best known of all extinct Quaternary animals, our knowledge being derived from abundant skeletons (sometimes complete, as at Borna near Leipzig), from palaeolithic drawings and engravings,[377] and from carcases in oil-bearing beds at Starunia in east Galicia[378] or frozen in Alaska[379] and Siberia (even the blood has been examined[380]). These carcases, when newly exposed, are eaten by bears, wolves, fox and dog, or are used as bait by the natives in setting their fox traps.

There are records of 37 accidental discoveries of the mammoth with its soft parts preserved[381] (fig. 151), including the first one described by P. S. Pallas in 1771. Only four carcases were in good condition; these were "Adam's mammoth" of the Lena delta (1806), "Herz's mammoth" of the Beresovsk River (1899), "Stenbock-Fermor's mammoth" of Great Lyakhov Island (1906), and "Vollosovitch's mammoth" of Sanga-Yurakh River (1907).

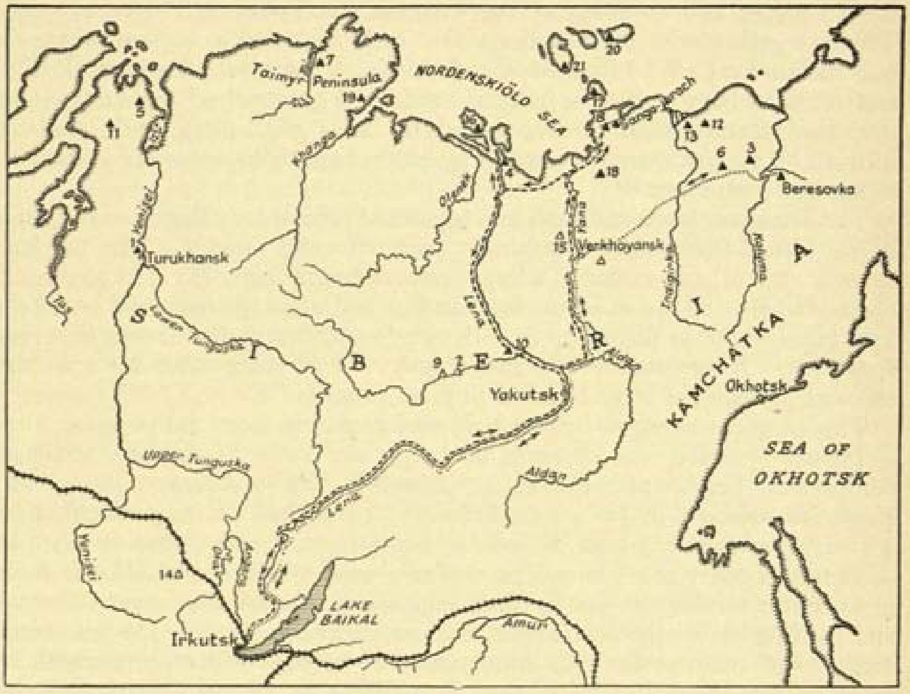

FIG. 151.—Distribution of known carcases of the mammoth and woolly rhinoceros in Siberia. F. W. Pfizenmayer, *Nat. Volk*, 67, 1937, p. 222.

.... Beresowka Expedition, 1901.
— — — — — — — Sanga-jurach Expedition, 1908.
▲ Mammoth. △ Woolly rhinoceros.

1. Mammoth of Isbrand Ides, 1707.
2. Rhinoceros (head) of Pallas from the Vilui, 1771.
3. Mammoth of Sarytschew, 1787.
4. Mammoth of Adams, 1799.
5. Mammoth of Trofimow, 1839.
6. Mammoth of Roschin, 1839.
7. Mammoth of Middendorf, 1843; cf. N. Polutoff, *E. & G.* 6, 1955, 152.
8. Mammoth from the Sanga-jurach, 1844.
9. Woolly rhinoceros from the Vilui, 1858.
10. Mammoth of Dr. Golubew, 1860.
11. Mammoth of Schmidt, 1864.
12. Mammoth of Maydell from Kowschetschja, 1869.
13. Mammoth of Maydell from Schandron, 1869.
14. Woolly rhinoceros of Tscherski, 1875.
15. Woolly rhinoceros (head) of Schrenck from Bytantai, 1877.
16. Mammoth of Bunge, 1884.
17. Mammoth of Toll from Great Lyakhov Island, 1885.
18. Mammoth of Toll from the river Tschendon, 1886.
19. Mammoth of Burimowitch, 1887.
20. Mammoth of Brusnew of the New Siberian Islands, 1902.
21. Mammoth of Wollosowitch from Kotelniyi Island, 1910.

From these sources it is possible to reconstruct not merely the osteology[382] but the whole animal.[383] The cover of hair[384] varied according to the season but was generally black or dark rusty brown, and composed of an outer coat of long coarse hair with a dense underfur and an epidermis identical with that of the modern elephant. Under the exceptionally thick skin was a layer of fat 9 cm thick. The hairy cover was a protection from the cold as Playfair[385] and later writers surmised, a conclusion borne out, according to Owen,[386] by the structure and covering of the extremely complex teeth (see p. 793). These, together with the peculiar tusks (early regarded as curved outwards but shown by E. W. Pfizenmayr and others to have varied a great deal[387] and often to have curved spirally inwards in a great wheel-like circle) and four-toed feet (instead of five found in other elephants), with phalanx formula[388] 0.2.3.2.2, are expressions of extreme specialisation and adaptations to marshy pasturages.[389]

The head was large and high and separated behind by a depression from a dorsal hump from which the hinder part fell away rapidly. The tail was short (*c.* 35 cm) and ended in a large tassle of bristly hair.[390] The proboscis resembled that of the modern elephant but had a heavy cover and bore two lips, represented in European cave-drawings and seen in one frozen Siberian specimen. Its greater width and length was an adaptation towards the efficient plucking of large bunches of grass or moss.[391]

The animal was more lightly built and probably more active than other elephants—possibly one cause of its longer survival. It was also small as comparative heights at the shoulder show[392]; *Elephas antiquus*, 4·1–3·8 m; *E. meridionalis*, 3·6 m (= 4·2 m, Falconer; 5 m, Abel); *E. trogontherii*, 4·0–4·5 m; *E. africanus*, 3·4 m; *E. indicus*, 2·7–3·2 m; *E. primigenius*, 3·2–3·9 m (skeleton, 2·9–3·7 m). It was particularly small where the conditions were most unfavourable, as in Europe, e.g. about Boden See, near Weimar and in Rhenish Westphalia during the last glaciation[393] and (though seemingly dwarf mammoths were contemporaries of the ordinary mammoth as early as late-Aurignacian in east Europe[394]) in North Siberia[395]—the Beresovsk mammoth was only 2·8 m high.[396] This species, the *E. beresovkius* of O. P. Hay[397] and *E. primigenius sibericus* of Depéret and Mayet,[398] was distinguished by its smaller skeleton and tusks,[399] features corresponding with its systematic position as the youngest member of the fossil elephant group.

That the mammoth was a cold animal is shown by its hair and fat (1–9 cm thick), the histological structure of its skin and the absence of sweat glands,[400] by the heavy rims around its hoofs (an adaptation to tundra marshes[401]), its small tail and ears,[402] the rapidly sloped hind quarters adapted to northern blizzards,[403] the fat humps in the swollen forehead and in the back (provision for periods of hunger), as seen in palaeolithic drawings and carcases,[404] and by its definite association with an arctic flora,[405] e.g. in Holland, at Borna in Saxony, near Freiburg-im-Br., in the Black Forest, near Halle, and at Starunia in Poland. Yet in the Petershöhle[406] in south Germany, at the time of the formation of the Weimar tufas, mammoth was associated with woolly rhinoceros and reindeer and with *Fagus sylvatica*, *Taxus baccata*, *Pinus sylvestris*, *Picea excelsa* and *Abies alba*, i.e. the forest flora of the present German Mittelgebirge. The great length and curvature of the tusks were clearly unsuited to life in arctic forests.[407] The animal lived on the northern grasses, obtaining in summer a good food supply, its large reservoirs of

fat being drawn upon during the winter seasons to eke out the meagre vegetation.

The mammoth wandered in herds like the modern elephant and spread widely through the middle latitudes of the northern hemisphere.[408] It was widespread in Siberia (see p. 648) and extended to Sakhalin[409] and as far south as 42° N. in Manchuria[410] (with *Tichorhinus antiquitatis*), and to the northern shores of the Caspian Sea and south of the Black Sea into Anatolia[411] and Armenia[412] and to Tarsus in the Mediterranean[413] (fig. 152). It was dispersed over south Russia[414] to the region of the Crimea and Caucasus (with other arctic animals,[415] including reindeer, arctic fox, arctic hare and glutton), and as far north as the White Sea, e.g. the Petschora basin, into the great valleys of central Europe, e.g. the Rhine, Danube, Theiss and Dniester, over the Hungarian plain, and into Jugoslavia, Rumania (with woolly rhinoceros, Giant Deer and reindeer) and Bulgaria.[416] It roamed with other arctic animals into Bohemia[417] and over the Swiss Plain (over 100 localities) to the mouths of the Alpine valleys[418] and even into them, as near Innsbruck.[419] Crossing the Seine and Somme and other French rivers into Haute-Garonne[420] and north Spain, as at Santander and Gerona, it invaded Italy,[421] for example, the Plain of Lombardy, Tuscany, Otranto, and near Caserta, but not Calabria or Sicily.[422] It has been found in many localities in Denmark.[423]

The mammoth was numerous in the gravels and caves of southern England and Wales[424] and extended into central Scotland[425] (Dreghorn, Clifton Hall, Ayton, Kilmaurs, Chapelhall, Bishopbriggs (with *T. antiquitatis*[426]), Baillieston and Headswood) and Ireland[427] (Co. Antrim, Co. Cavan, Co. Waterford, and Co. Cork) and has been dredged from the floor of the North Sea (see p. 1230), Irish Sea (Holyhead Harbour), and Galway Bay in western Ireland.

It has been recorded from South America (see p. 1238) and in the Vaal valley of South Africa with palaeolithic implements[428] (*Mammuthus transvaalensis* and *M. sheppardi*)—this more probably belongs to the family of *Elephas meridionalis*.[429] It was also common in the middle latitudes of North America[430] (fig. 150, p. 805) and in Alaska and the Yukon Territory[431]; one tusk has been found in Banks Island off north Canada.[432]

The mammoth consisted of two types,[433] the "normal" or "ancient type" and the "Siberian" or "recent type" (*E. primigenius sibericus* de Blainv.), distinguished among other ways (see above) by its more numerous lamellae and thinner and more continuous enamel. This either descended from the normal type, as is generally believed, or evolved independently in north Asia.[434] It was especially characteristic of the Magdalenian. Others[435] have contended that the division into two types is unwarranted, the *sibericus* forms having neither racial nor chronological value.

Woolly rhinoceros. The woolly (or better, hairy) rhinoceros, *Tichorhinus antiquitatis* Blum, has, like the mammoth, been reconstructed[436] from skeletons, from palaeolithic drawings, e.g. that of Font-de-Gaume,[437] and, less commonly than in the case of its contemporary, from carcases (probably because it preferred solitude to roaming in herds[438]). These occur both in the frozen ground of Siberia,[439] e.g. "Pallas's rhinoceros" (1771) of the Vilui River, and "Gorokhov's rhinoceros" of the Khalbugai Creek (1878) or (two carcases) preserved by petroleum and salt-water with molluscs, insects and mammoth at Starunia.[440]

The hair was thick and reddish-brown[441] and covered a foldless skin.

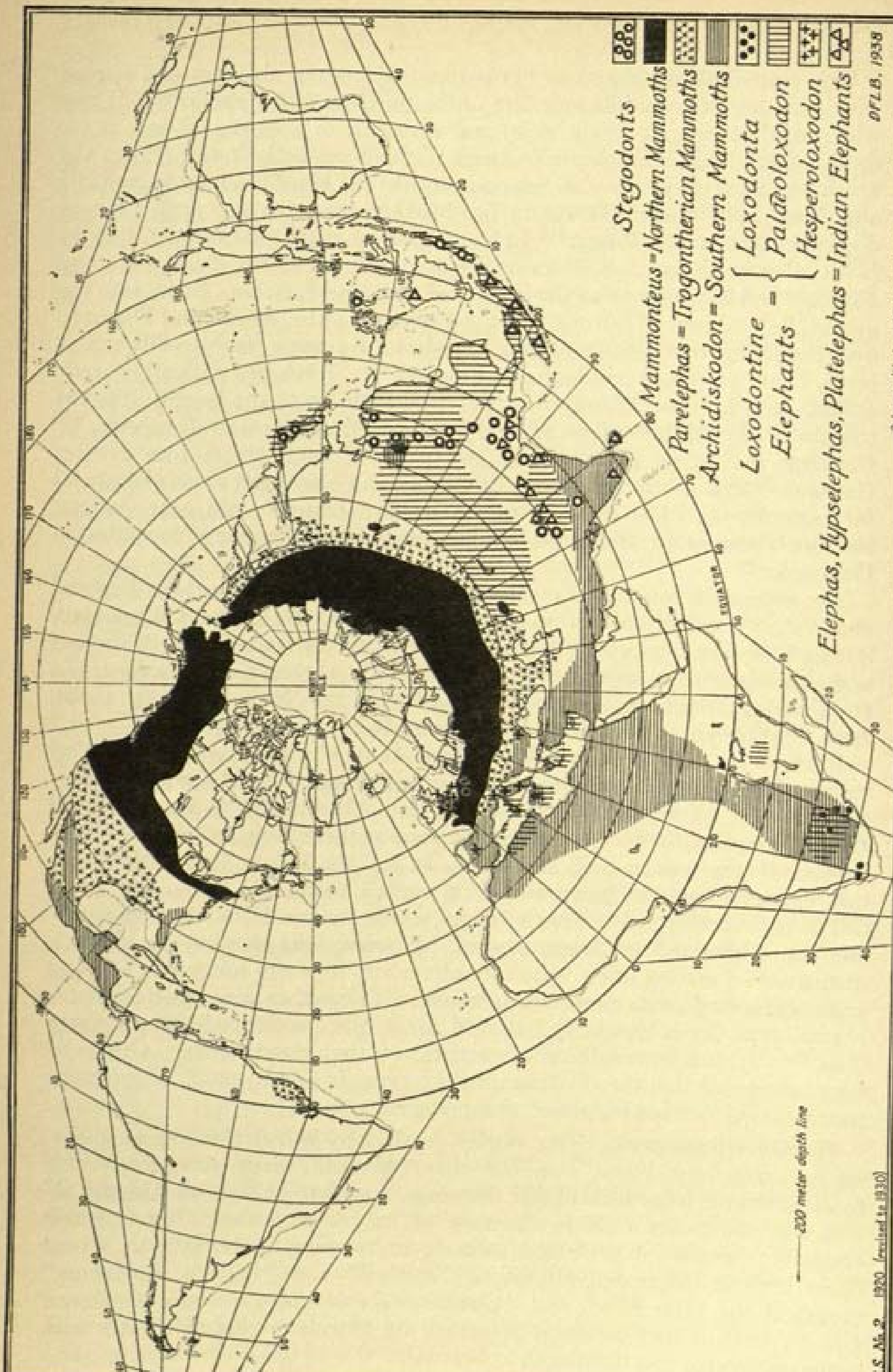

FIG. 152.—General climatic distribution of the subfamilies of the Elephantoidea and Stegodontoidea. H. F. Osborn, 1233, II, p. 914, fig. 795.

The animal was stout limbed and massive, and had a complete osseous nasal septum to support the two short horns (1·2 cm long) which were used to search for food, especially in winter—the horns were not bony but merely hardened clusters of hair. Like the mammoth (see above), it probably had a "fat hump" provided with reserve food.[442] The tuft at the extremity of the tail of the Starunia specimen was used to swat flies and other insects.

This rhinoceros, which seems to have lived nearer the ice than did the mammoth,[443] and, judging by its skull form, to have fed on tundra and similar low-growing vegetation,[444] ranged widely over north Asia to the arctic shores and the Bering Sea, and into north Manchuria,[445] Mongolia and north China as far as the zoological frontier of the mountains south of the Yellow River.[446] It likewise spread to the Caspian Sea and in Europe to Rumania[447] (it is absent from the Balkans), Jersey[448] and to Britain[449] in the west, to Lübeck in north Germany,[450] and over the Swiss Plain[451] (13 localities) to the Alps and Pyrenees. Its southernmost outposts were in Catalonia[452] and Italy,[453] e.g. near Rome and in Otranto.

Great Irish deer. *Megaceros giganteus* (= *M. hibernicus* Owen), which was characterised by its large size, heavy build and large, more or less palmated antlers, was probably descended from the ancestral Fallow Deer of the upper Pliocene[454]—*Cervus senezensis* occurred in the oldest Pleistocene, *C. giganteus süssenbornensis* in the lower Pleistocene and *C. giganteus antecedens* in the middle Pleistocene. Its extreme variability has led continental authorities to found a number of races or species. Five subspecies have been distinguished[455]; *C. giganteus typicus* (= *C. hibernicus*), *C. ruffi* (= *C. germanicus*), *C. italiae*, *C. belgrandi* and *C. cornotum* (of the Cromer Forest Bed), the systematic value of which is uncertain.[456] Soergel,[457] who sketched the development of the Giant Deer, created a new subspecies, *C. megaceros mosbachiensis*, and recognised *C. megaceros verticornis*, *C. megaceros germanicus* and *C. megaceros hibernicus*.

The Giant Deer, with antlers 3·5 m across, was especially abundant in Ireland[458] (e.g. plain of Limerick, near Tuam, Lough Derg shore, Killowen, Co. Waterford, and Ballybetagh Bog, Co. Dublin) but was found elsewhere in the British Isles[459] and over most of Europe[460] including Italy (it was plentiful in the Po Plain[461]), Germany (the remains are said to belong to *C. germanicus*[462]) and south France. It also extended to the Caucasus, the Urals and the Altai caves.[463]

Arctic rodents. The minor arctic species, such as *Lepus variabilis*[464] (arctic hare), *Lemmus lemmus* (Norwegian lemming), *Dicrostonyx torquatus* (snow lemming)—the two lemmings have probably a common ancestor[465]—*Arvicola ratticeps* (northern vole) and *Alopex lagopus* (arctic fox), were formerly much more widely distributed. E. Bayer[466] has listed and mapped the European localities of, among other animals, the lemmings, arctic fox and bears. The importance and distribution of the rodents were discussed by Nehring.[467] The lemmings in particular migrated far over central and western Europe (see p. 1037) to Denmark,[468] Hungary,[469] Dordogne,[470] Portugal,[471] north England[472] (Erewash valley, Langwith Cave, Warton Crag, Creswell Caves, Dog Holes Cave, Ightham fissures), Ireland[473] (Kesh, Edenvale, Castlepook, Lough Gur, Kilgreany) and to Jersey (St. Brelade Cave), and Edinburgh[474] and Inchnadamph (p. 1011). They were often accompanied by pika or tailless hare, a close ally of which inhabits the Volga district, Ural

Mountains and Siberia as far as the River Ob. It has been found in about 17 German and 3 Belgian caves of Magdalenian age and in several British caves.[475]

The distribution of the arctic fox, *Alopex lagopus*, was practically that of the reindeer (see above). Now restricted to the north circumpolar region, its Pleistocene range was over north Germany and central Europe into Moravia[476] and to Kiev and the Crimea in Russia[477] and as far west as

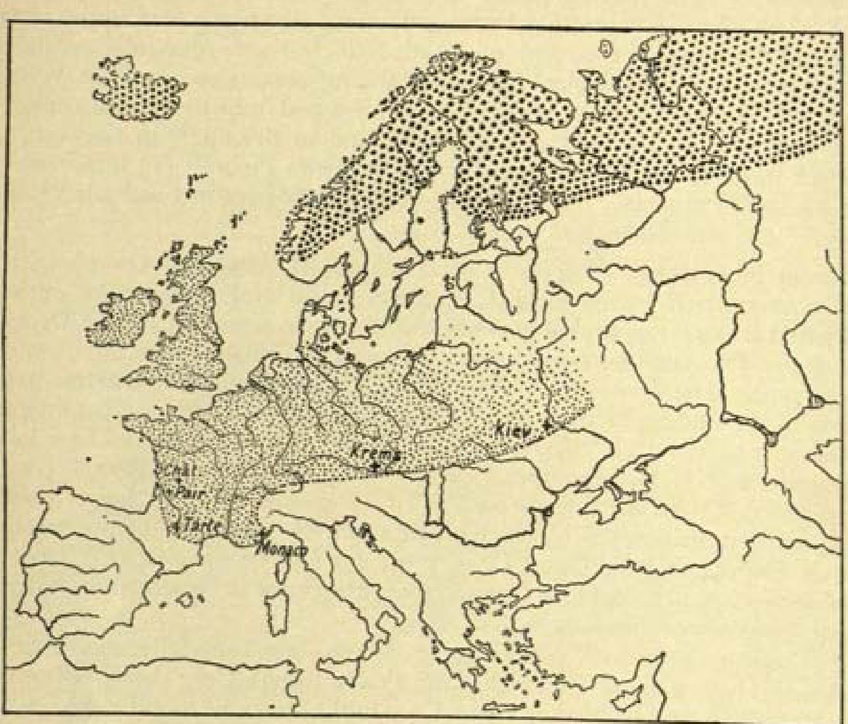

FIG. 153.—Distribution of the arctic fox in Europe to-day (large dots) and during the Glacial period (small dots). M. Boule, *175*, p. 71, fig. 13.

England[478] (Creswell, Fisherton, Ightham and Walton) and Ireland[479] (Ballinamintra, Doneraile, Kilgreany) and as far south as the Pyrenees,[480] Monaco[481] and Switzerland[482] (fig. 153).

The arctic hare too was widespread: it was abundant, for example, in Britain[483]—*Lepus europaeus L.* or *europaeus* L. var. *anglicus* Hinton[484] is a more recent introduction.

(*d*) *Alpine Mammalia*

The Alpine mammals, *Capra ibex* (ibex), *Rupicapra rupricapra* (chamois), *Arvicola nivalis* (Alpine vole) and *Marmota marmota* (Alpine marmot), came down from their present restricted habitats to the surrounding plains. They are represented, for example, in Magdalenian drawings and sculptures in south France and Spain.

The ibex, or mountain goat, divisible into more than one species[485] but of uncertain origin, spread far from the Alps (*C. ibex*) and Pyrenees (*C. pyrenaica*)

into France (Les Eyzies, Laugerie-Basse, Bruniquel, Aurensan, Brittany, etc.) and Belgium,[486] to the middle Rhine and Thuringia,[487] Bohemia,[488] Jugoslavia,[489] and to Santander,[490] Burgos,[491] Gibraltar,[492] Monaco,[493] Liguria[494] and south Italy[495] (fig. 154).

The chamois,[496] which as L. Rütimeyer showed was subdivided in the Pleistocene into a Pyrenean and an Alpine race (Grimaldi had a mixed type[497]) and, like the ibex, may have descended from some unknown Asian ancestors,[498] extended over much of Europe[499] (fig. 155), viz. to the plains at the foot of the Pyrenees,[500] on both north and south, e.g. at Santander and

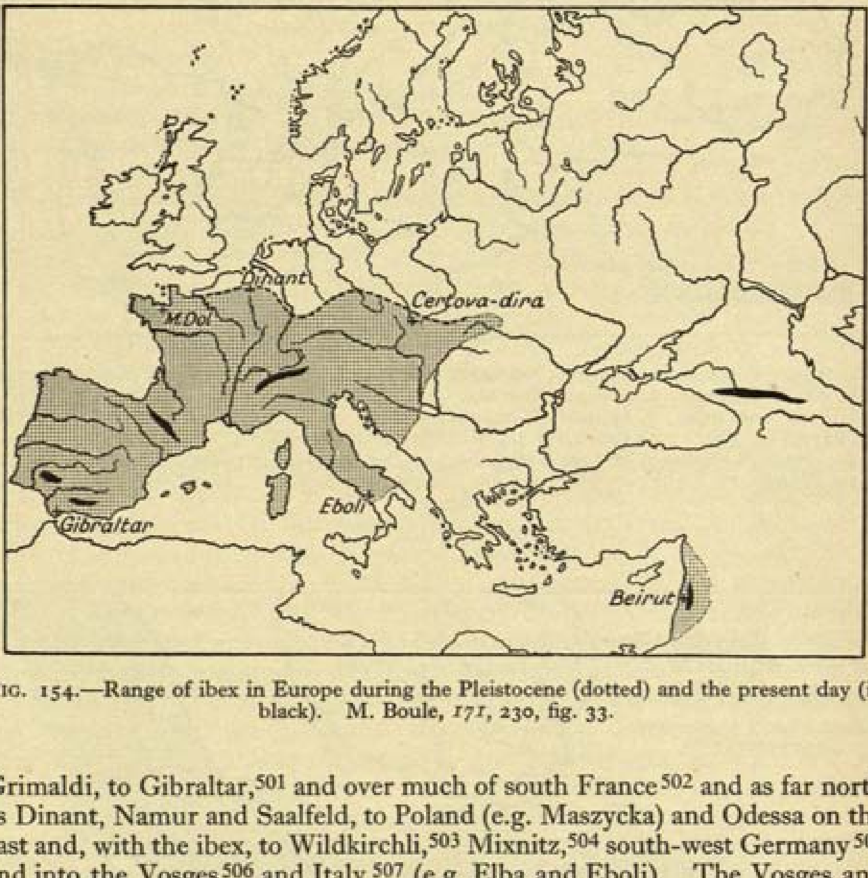

FIG. 154.—Range of ibex in Europe during the Pleistocene (dotted) and the present day (in black). M. Boule, *171*, 230, fig. 33.

Grimaldi, to Gibraltar,[501] and over much of south France[502] and as far north as Dinant, Namur and Saalfeld, to Poland (e.g. Maszycka) and Odessa on the east and, with the ibex, to Wildkirchli,[503] Mixnitz,[504] south-west Germany[505] and into the Vosges[506] and Italy[507] (e.g. Elba and Eboli). The Vosges and Black Forest had colonies of the chamois in the late-Pleistocene.

The Alpine vole has been traced south of the Alps to the Côte d'Azur, Brescia, Pisa and the islands of Palmaria, and north of the Alps into the Bohemian Forest, to near Budapest, to Bavaria (upper Franconia), Schweizersbild, Kesslerloch and Mauberge[508] and into the Thames valley.[509] The Alpine marmot has been found over much of central Europe[510] (fig. 156), in the caves of Wildkirchli, Drachenloch and Wildenmannisloch, in Castillo and La Peña (Asturias), and on the Po Plain and the Ligurian coast.[511] It has been discovered in Moravia[512] and the Rhine valley (Eifel) and German lowlands[513] and in the Seine valley and Brittany.[514]

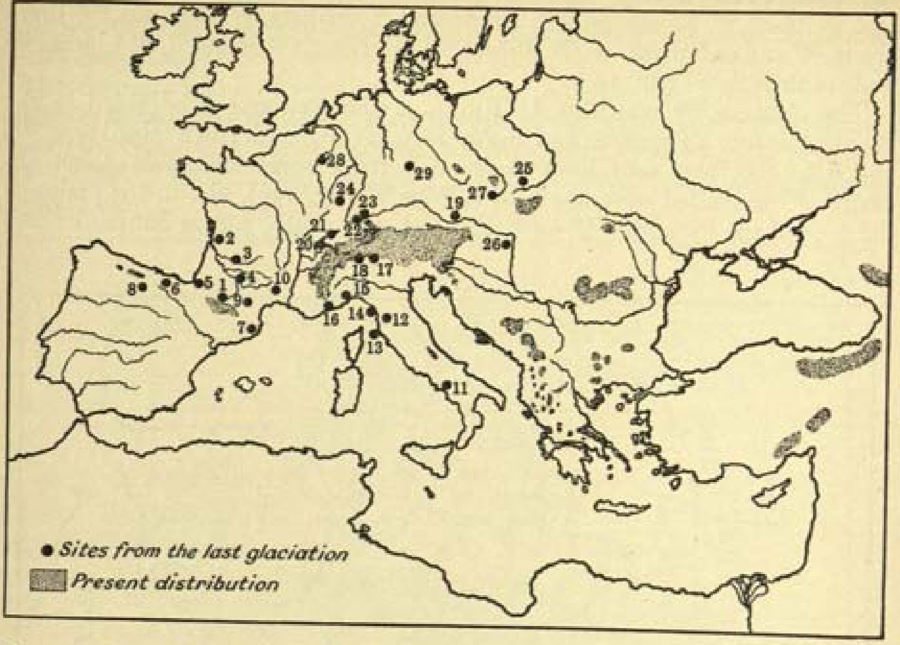

FIG. 155.—Range of the chamois, *Rupicapra rupicapra* L., in Pleistocene and Recent Europe. 1, Haute-Garonne; 2, Ariège, Charente, Gironde; 3, Dordogne; 4, Garonne; 5, Isturiz; 6, Prov. Santander; 7, Gerona; 8, Burgos; 9, Bize; 10, Languedoc; 11, Eboli; 12, Monti Pisani; 13, Elba; 14, Palmaria; 15, Liguria; 16, Grimaldi; 17, Lavrange; 18, Como; 19, Lower Austria; 20, Jura; 21, Cotencher; 22, Schaffhausen; 23, Black Forest; 24, Vosges; 25, Poland; 26, Sipka; 27, Moravia; 28, Namur; 29, Saalfeld. H. Wehrli, *1918*, p. 252, fig. 111.

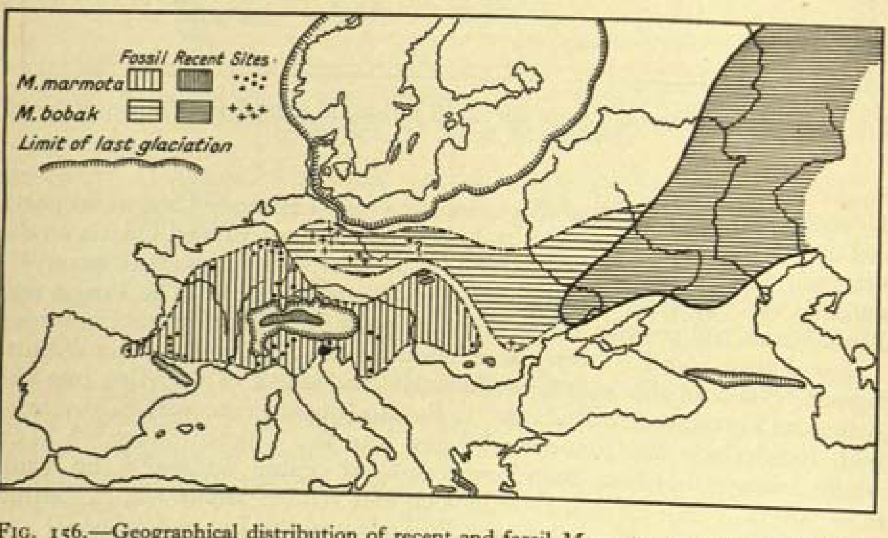

FIG. 156.—Geographical distribution of recent and fossil *Marmota marmota* and *M. bobak* in Europe. O. Tschumi, *1918*, p. 255, fig. 115.

Age and Succession

Basis of succession. A mammalian succession during the Pleistocene is shown by the superposition in river-terraces and caves: different layers have different assemblages. This capital fact escaped the notice of earlier investigators who, besides ignoring the microfauna, listed together all species obtained from a particular site. Yet superposition in a cave is not always a rigid test[515]; layers may be re-arranged by floods, by stream excavation and deposition, by burrowing badgers, rabbits or rats, and by the successive tenants, including palaeolithic and later man.

E. Lartet[516] established a four-fold succession based upon the successive and universal disappearance of animals in caves and river-deposits:

4. *Bison europaeus*.
3. *Rangifer tarandus* ("Reindeer period").
2. *Elephas primigenius* and *Rhinoceros antiquitatis* ("Mammoth period").
1. *Ursus spelaeus* ("*l'Epoque du grand ours des cavernes*").

F. Garrigou[517] prefaced this succession with the epoch of *Elephas antiquus*, with *E. antiquus*, *Rhinoceros merckii* and *Hippopotamus amphibius*. Other palaeontologists founded their successions upon members of Cuvier's group of the Pachydermata. Thus Osborn[518] obtained the following rhinoceros succession: *Rhinoceros etruscus* (First interglacial), *R. mercki* (Second and Third interglacials) and *R. antiquitatis* (Fourth glacial), and H. Pohlig[519] distinguished the stages of *Elephas meridionalis*, *E. trogontherium*, *E. antiquus* and *E. primigenius*.

Nevertheless, such successions have been denied.[520] They are, it is objected, incompatible with a repetition of glacial and interglacial epochs and faunas or with variations in latitude. Moreover, the animals assigned to different periods were in fact contemporaries, e.g. cave bear and mammoth, reindeer and mammoth, and *Rhinoceros leptorhinus* and *R. antiquitatis*.

A mammalian succession is, however, incontrovertible. It is warranted by the state of preservation of the bones and their degree of alteration, as well as on archaeological grounds, e.g. the fairly constant association of Mousterian implements with mammoth and of the Magdalenian with reindeer. Early writers recognised that the group *R. etruscus*, *E. meridionalis*, *Machairodus* and *Equus stenonis* preceded the *faune chaude* of *Rhinoceros leptorhinus*, *Elephas antiquus* and *Hippopotamus*[521]; that *Elephas antiquus* preceded *E. primigenius*[522]; and that the *faune chaude* preceded the cold animals, namely mammoth, woolly rhinoceros and reindeer.[523] The "Reindeer period" of French archaeologists has been generally recognised—Dawkins[524] probably alone dissented. G. Dubois[525] has recently sought to establish a rodent succession for the Pleistocene of west Europe.

A recent view largely discounts the reality of alternating "cold" and "warm" faunas (e.g. p. 902) and regards the development of the Pleistocene mammals as a continuous process with only minor climatic fluctuations.[526] In North America too it is thought there was very little gradual and progressive extinction during the Pleistocene,[527] the persistence of forms being more complete than in Europe. In South America also the range of the Pampean mammals is for the most part continuous, both the autochtonous genera (e.g. the edentates and certain of the noto-ungulates) and the immigrants (e.g. *Arctotherium*, *Canis*, *Smilodon*, *Hippidion*, the artiodactyls and the

proboscideans) showing this feature.[528] The giant herbivores of Australia also survived into Recent time when their own gigantism, the increasing aridity, and the advent of the dingo led to their extinction.[529]

European succession. Several reconstructions, elaborations of those of earlier palaeontologists, have been made. E. Koken[530] found the following succession: 1. Pliocene; 2. *Elephas antiquus* and some Pliocene forms (St. Prest, Cromer Forest Bed, Mosbach, Mauer, Süssenborn, Erfingen); 3. *E. antiquus* (Chellean); 4. *E. primigenius*; 5. *E. antiquus* with *E. primigenius* (Taubach, older loess of Achenheim, Cannstadt); 6. *E. primigenius* (Rixdorf, lower rodent layer); 7. Horse epoch (recent loess); 8. Reindeer fauna (upper rodent layer); 9. Deer.

J. Bayer[531] recognised the following:

4. *E. primigenius* Fauna (Riss and Würm and Aurignacian oscillation).
3. *Rhinoceros merckii* fauna (Chellean, Lower Acheulian; Taubach, Mauer).
2. *Elephas antiquus* fauna; *Rhinoceros etruscus* fauna (Pre-Chellean; Mosbach, Mauer, Cromerian).
1. *Elephas trogontherii* fauna (Süssenborn, Mosbach).

W. Soergel[532] built up the following faunal succession:

I. Upper Pliocene, e.g. Val d'Arno, Mosbach I. Perrier, Puy, Dove Holes (Derbyshire) and part of Cromer Forest Bed.

Mastodon arvernensis, Elephas meridionalis, Machairodus sp. *Rhinoceros etruscus, Equus stenonis, Hippopotamus, Ursus arvernensis, Hyaena arvernensis, H. perrieri, Antelopes* and the following Cervidae, *Cervus elephas, C. axis, Capreolus, Eucladocerus.*

II. St. Prestian of C. Depéret[533] who recognised the three Pliocene faunas of Montpellier, Perrier and St. Prest, with a large faunal list,[534] including four Pliocene species (*Elephas meridionalis, Rhinoceros etruscus, Hippopotamus, Equus stenonis*) and four new species, all of large size, *Cervus dupuisi, Elephas* sp., *Alce,* cf. *latrifrons* and *Bison priscus*—Mastodont is missing.

This horizon, which also occurs with Pliocene animals in the lowest horizon at Abbeville[535] and in Hungary[536] is that of the *meridionalis* fauna of Mosbach II and of St. Martial, Rossières and part of the Cromer Forest Bed.

III. First Interglacial Fauna (Günz-Mindel) at Süssenborn, Amiens Upper Terrace, Mosbach III, part of Cromer Forest Bed, Mauer, all differing slightly among themselves—the Cromerian has other faunal equivalents in Europe[537] (see p. 949).

The animals are those of St. Prestian minus *Elephas meridionalis* and including new forms, *E. trogontherii, E. antiquus, Rhinoceros merckii* and *Elephas mosbachiensis.*

The following broad trend is readily recognisable.[538] A lower Pleistocene fauna consisting of Pliocene survivors with primitive elephants and small horses (Norwich Crag, lower Val d'Arno, Villafranchian, Sanmen I). A middle Pleistocene fauna containing true Pleistocene elephants (*E. antiquus* of Eurafrica, *E. namadicus* of Asia) with larger horses (Cromer Forest Bed, Champs de Mars, Mauer, Mosbach, Süssenborn, upper Val d'Arno, Lower Karewa and Sanmen II). An upper Pleistocene fauna which enters with the extinction of this fauna more or less simultaneously all over the Old

World. This includes the cold fauna of mammoth, woolly rhinoceros, etc. In Europe this change may be expressed as follows:

Glacial IV.—Extinction of *Elephas primigenius, Tichorhinus antiquitatis, Crocuta spelaea, Ursus spelaeus.*

Interglacial.—Extinction of *Elephas antiquus, Diceros leptorhinus, Felis spelaea.*

Glacial III.

Interglacial.—First appearance of *Bos primigenius, Rangifer tarandus, Tichorhinus antiquitatis, Crocuta spelaea, Ursus spelaeus.*

Glacial II.—Extinction of *Hyaena arvernensis, Equus robustus, E. stenonis, Dicerothinus etruscus, Elephas meridionalis.*

Glacial I.

The Neolithic witnessed the entry of domestic animals into Europe, as Swiss investigations show.[539] These animals, notwithstanding instances cited from upper palaeolithic horizons in north-west Europe,[540] were apparently absent from the Pleistocene—this has been asserted, for example, for sheep, goat, dog and *Bos longifrons* for the British Isles[541] and there is no clear evidence to support the claim[542] (made on account of certain markings on the engraving of horses) that Magdalenian man bridled the horse.

More recent times have seen the extinction or great diminution of such animals as the bear, wolf, wild cat, lynx, wild horse, elk, aurochs, otter, wild boar and red deer as the result of man's activities (cf. p. 1398).

European time-range. The widespread faunal changes of the Pleistocene consisted of the extinction of old forms, the immigration of new forms and the evolution of more primitive species into more advanced species *in situ*. Animals appeared and disappeared after a time-range which varied with the animal[543] (fig. 157) and with the region—a table showing the time-range of 70 mammals has been given for Russia.[544] Thus *Trogontherium cuvieri* did not outlive the Günz-Mindel interglacial in central Europe but in west Europe straddles the Mindel-Riss. Hippopotamus appeared suddenly in Europe in the lower Pliocene, e.g. at Gravitelli in Sicily[545] and ranged through the Cromer Forest Bed, Tegelen, St. Prestian, Leffe, Mosbach, Mauer and the Rixdorf interglacial. It disappeared from Europe before the Mousterian or Aurignacian as did *Elephas antiquus* (which reached the last interglacial in north Germany) and from North Africa about the same time, i.e. before the Capsian (Gétulian) industry. Hippopotamus probably survived later in the west and south than in central Europe. Its disappearance in Palestine was of the same date[546] though it survived at the mouth of the Nile into the Middle Ages. The meridional elephant ranged from the Norwich Crag and the tufas of Leffe[547] into the Cromerian (*E. meridionalis* mut. *cromerensis*[548]). The cave lion is absent from the Pliocene and Cromer Forest Bed[549] but, as a contemporary of the mammoth, characterised the Mousterian.[550] It survived into the Alpine Palaeolithic and the Magdalenian, as remains at Kesslerloch and paintings show,[551] and in fewer numbers and smaller dimensions into the Azilian,[552] as well as into recent times in Greece and Asia Minor according to Herodotus and Aristotle.[553] The panther lived at Mosbach and Mauer in lower Pleistocene time, was widespread during the Mousterian, occurred at Wildkirchli, Drachenloch, Cotencher and Schnurenloch, but failed apparently to survive the Aurignacian.[554] Lynx on the other hand extended upwards into the Magdalenian[555] and into the lake-dwellings.[556]

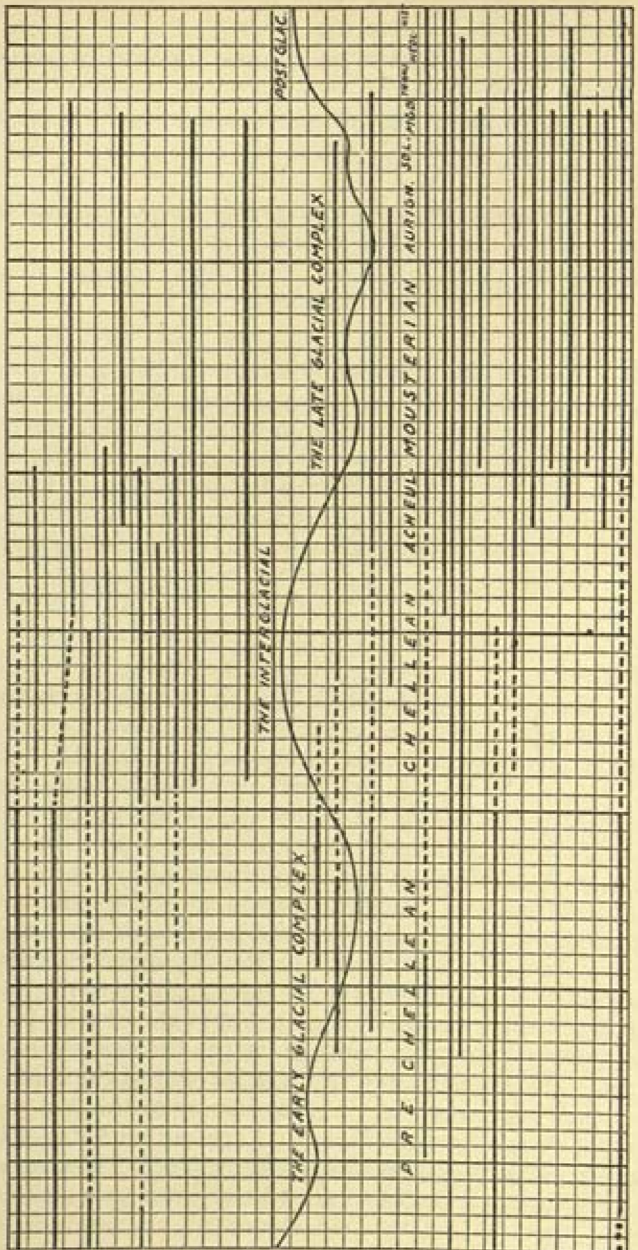

FIG. 157.—Time-range of the European Pleistocene mammalia. A. Hrdlicka, *Sm. I. Rp.* 1928, p. 123, fig. 2.

The cave hyaena, which like the cave bear was not a true cave type in the lower beds but its ancestor[557] (some authors[558] attribute the early Pleistocene bears to *Ursus deningeri*), extended from the Cromerian to the Magdalenian of Kesslerloch, though it is unrepresented in Magdalenian Art. The cave bear also appeared in the Cromerian and is in the oldest layer of Kent's Cavern[559] and in the Creswell Caves—it also occurred in the deposits at Cannstadt—but was the characteristic fossil of the upper Pleistocene, of the Swiss *Schieferkohlen* and of the last interglacial or *Ursian* epoch,[560] during which it was numbered in hundreds of thousands and reached its greatest size and widest variation—in the Drachenhöhle near Mixnitz it was associated during Riss-Würm time with *Pinus nigra* and *Fagus*.[561] It persisted from the Chellean into the Magdalenian, as at Birstal and Sirgenstein.[562] It has, however, been contended that the cave bear died out in the Aurignacian or Solutrean,[563] a statement which clashes with the graphic representation of the animal in some Magdalenian caves of south France[564] and is only so far true that the animal which died out during the last glaciation[565] was certainly much rarer after the Solutrean and, as in the Mixnitz Drachenhöhle and "Alpine palaeolithic" caves (see p. 1035), became progressively smaller[566] with the oncoming glaciation during which it died out. The brown bear, *Ursus arctos*, may range back into the last or the penultimate interglacial. It inhabited Sweden into the hazel period[567] and has been found in postglacial Denmark[568] (21 localities) where it lived in the milder Alleröd period and up to the close of the neolithic and mixed oak forest period. Its remains are not seldom in the earlier Swiss lake-dwellings.[569]

The musk ox lived from Cromer Forest Bed time (see p. 995)—*Praeovibos*, an ancestral form, is found in the lower Pleistocene gravels of Mosbach and Süssenborn[570]—and occurred in Mindel times in Bavaria and Swabia.[571] However, it only became a really characteristic member of the Pleistocene fauna when the tundra mammals spread farther south during the lower Magdalenian, for the majority of the German and Swiss occurrences belong to the last glaciation[572]; it may (doubtfully) have survived to 2000 years ago in north Mongolia.[573] Arctic fox and glutton ranged from the Mousterian onwards,[574] the latter occurring with middle Magdalenian implements in Belgian caves, and with late Aurignacian or Magdalenian relics in Germany.

The *trogontherii* elephants disappeared about the last interglacial period. The mammoth lived from Acheulian or the second half of the Mindel-Riss interglacial epoch[575] (its presence in the Cromer Forest Bed is disputed; see p. 995) into the late-Magdalenian[576] or Swiss Bühl stage.[577] It preceded the Chalky Boulder-clay of East Anglia[578] but apparently existed to a later date in Silesia, Poland and Russia[579] and into recent times in Siberia[580] where, at Tomsk, its skeleton was found associated with human debris[581]—the claim that it survived into postglacial England[582] is not justified. Its companion, the woolly rhinoceros, extended from the Cromerian,[583] the Ilford horizon in the Thames, and the interglacial horizon of Ehringsdorf[584] to early Magdalenian and the Laufen oscillation near Radolfzell in the Boden See area[585] and died out before the mammoth in north Asia.[586]

The reindeer began in the Chelleo-Acheulian epoch, e.g. at Mauer (it was missing from the Cromer Forest Bed) and lived with *Elephas trogontherii* and *Dicerorhinus etruscus* at Süssenborn[587] and in Swabia.[588] It was abundant in the lower Magdalenian but became rare in the middle and upper Magdalenian. Though absent like other arctic species from the Mas d'Azil and

other French Azilian stations[589] and from the later Azilian in Britain[590] it ranged to the close of the Magdalenian in south Germany[591]—it was abundant in lateglacial time in East Prussia[592]—into the Gschnitz stage and Azilio-Tardenoisian[593] in Switzerland (it wandered into the Alpine valleys) and the Tardenoisian (= upper Palaeolithic ?[594]) in the grotte de Remouchamps, Belgium.[595] It disappeared from Leningrad and the Baltic provinces during the Dryas period[596] but persisted in Scania, Pomerania and at Kunda and Skipsea (Yorkshire) into the early part of the postglacial forest period[597] (Boreal and Boreal-atlantic transition) and in central Europe into the times of Alexander and Caesar.[598] It lived in the Subarctic period in Ireland[599] and wandered northwards in Britain into north Yorkshire (Kildale) and Scotland,[600] e.g. Dumbartonshire, Lanarkshire, Ayrshire, Midlothian, West Lothian, Stirlingshire, Perthshire, Sutherland (Inchnadamph), Ross-shire, Caithness and Orkney Islands. The alleged survival in Caithness until A.D. 1159,[601] based upon incidental notes in *Orkneyinga Saga*, is difficult to reconcile with its absence from neolithic Scotland and with other facts.[602]

The Giant Deer which was represented by several races in the Cromerian (see p. 995) inhabited Europe with the *faune chaude* and persisted longer than most Pleistocene animals—its survival of the "Deluge" in the Isle of Man was early demonstrated.[603] It lived on into the Gschnitz stage and pine period in Switzerland[604] and the period of the lake-marls (it was absent from the lake-dwellings), into Alleröd time in Ireland, Denmark and Scania,[605] into historic time in south Russia[606] (*c.* 500 B.C.) and died out before the Sub-atlantic period in both Ireland and Scotland.[607]

The red deer, *Cervus elephas*, found in the Cromerian, was plentiful when warm or wooded conditions prevailed. It was common during the Chellean and Aurignacian but became rare during the lower Solutrean and abundant once again in upper Magdalenian time, finally supplanting the reindeer in all French stations save in the extreme north.

The elk,[608] *Alce latifrons*, present in the Cromerian, lived throughout the older Pleistocene in northern and central Europe, while *A. alces* of later time lived in central Europe into historic time, and roamed as far south as Rumania, north Italy and the Pyrenees. The roe deer,[609] *Capreolus capreolus*, which appeared as early as the Miocene in Europe and lived in the Cromerian, ranged through the Pleistocene into, for example, the time of the Swiss lake-dwellings.

Citellus rufescens ranged in France from Acheulian to Magdalenian, appeared in England in the Cromer Forest Bed and survived in Denmark into the Alleröd period. *Equus stenonis*, which ranged upwards from the Villafranchian, died out in the Riss period (when *E. caballus* appeared), except in north France and Germany where it survived into the Würm.[610]

The bison, *Bison priscus*, generally recognised as a descendant of *B. sivalensis* Falc. and the ancestor of *B. europaeus*,[611] appeared in the Acheulian, was plentiful during lower Magdalenian, grew scarce during the middle and upper Magdalenian, and persisted through the Ancylus period in Östergotland.[612] It survives now only in the Caucasus. *Bos primigenius*, which was of south Asian descent—*B. planifrons* of the Siwalik Beds was an early representative—and appeared in Mindel-Riss times, e.g. in Germany,[613] ranged through the later Pleistocene over almost the whole of the Old World, becoming gradually smaller, and lived on into the 14th century in Germany, Poland, Hungary and Russia: it died out in 1627 (in Poland) but contributed to the present bovine races.

The ibex and chamois are first definitely known from the last interglacial epoch.[614] They became most widespread in Würm times and were only sporadic in the lake-dwellings.[615]

North American succession. The Quaternary mammalia of North America, which have a complete bibliography,[616] form a combination of faunas of different latitudes.[617] They include animals from Eurasia, e.g. *Mammuthus primigenius*, *M. trogontherioides* (*Parelephas washingtonii*, *P. jeffersoni*, *P. progressus*), *Rangifer tarandus*, *Ovibus moschatus*, *Bison*, *Ursus arctos*, *Castor fiber* and the large felines; an autochtonous fauna of mixed derivation from the Tertiary, e.g. *Mammut ohioticus*, *Equus caballus* and tapirs; and migrants from South America, found generally in the southern part of North America, e.g. the edentates of the genera *Megalonyx*, *Megatherium* and *Mylodon*.

This fauna died out gradually and at different rates in different places: the vast refuges of the mammals in the south make impossible the clear demarcations which characterise Europe. Hence, there is at present no general agreement as to the basis to be used in correlating the Pleistocene faunas of North America.[618] Nevertheless, the work of B. Brown, E. D. Cope, W. H. Hall, W. D. Matthews and H. F. Osborn[619] has established five successive mammalian faunas: an upper Pliocene or *Mammuthus imperator* fauna; an early Pleistocene (*Equus-Megalonyx*) fauna of *Stegomastodon mirificus*, *Mammut americanus*, *Mammuthus imperator*, *M. colombi*, *Tapirus*, with *Puma* and *Camelus* and several *Equus* species; a middle Pleistocene fauna of *Mammut americanus*, *Mammuthus colombi*, *Tapir americanus*, *Ursus americanus*, *Cervus canadensis* and *Alces*; a late-Pleistocene (*Ovibos-Rangifer*) fauna of *Ovibos moschatus*, *Rangifer tarandus*, *Mammuthus primigenius* and *Ursus americanus*; and a postglacial *Cervus* fauna—the horned ruminants of North America have been well monographed.[620] J. Bayer[621] correlated these five faunas with the *Elephas meridionalis*, *E. trogontherii*, *E. antiquus*, *E. primigenius* and the forest faunas of Europe.

Hay,[622] who had established a faunal succession for North America and maintained, contrary to the general view, that many North American animals were exterminated before the Wisconsin (even before the Kansan) glaciation, stated that each glacial and interglacial epoch took toll of the species. Camels, for instance, are not found in the interglacial epoch succeeding the Aftonian and horses, which numbered at least ten species, grew fewer as the Pleistocene advanced, failing to survive the Wisconsin. Other animals survived all the climatic changes; mastodonts have been found on late-Wisconsin drifts on Long Island and Staten Island[623] and with elephants, musk ox, moose, peccaries and giant beaver, survived into Recent times since, being found near the present shores,[624] they could not have lived where they are now found until almost all the postglacial uplift had taken place (see ch. XLV) and the ice had completely vanished from the Great Lakes. Mastodont apparently persisted into the 4th century A.D. in Ecuador.[625]

Evidence[626] appears to indicate that *Equus*, *Tapirella* and *Tanupolama* existed much later than the limits assigned by Hay.

It is interesting to note that many groups and families, e.g. ground sloths, Californian lion, mastodont and mammoth, certain peccaries, camel, musk ox, bison and giant beaver, lived on in America after they had become extinct in Europe.[627] This may be explained, though somewhat doubtfully, by the

late arrival of man who only at this stage was able to participate in the extinction of this fauna[628] (see p. 865).

African succession. East Africa provides the following mammalian succession[629]:

Upper Pleistocene: modern fauna with the African elephant as a late invader.

Middle Pleistocene: *Elephas antiquus recki* and *Hippopotamus gorgops.* Occasional survivals of earlier Chalicotheres, Mastodonts and Deinotheres.

Lower Pleistocene: *Stegodon*, primitive elephants of *planifrons* and *meridionalis* type, and two species of hippopotamus (*Hippopotamus gorgops, H. imaguncula*), Chalicotheres rare, but Mastodonts and Deinotheres not infrequent.

One or two genera of the Hipparion group occur in the lower and middle Pleistocene and zebras throughout the period.

The Omo Beds[630] of the country west and north of Lake Rudolph contain fishes closely related to or identical with living Nilotic species, reptiles, chelonians and crocodiles belonging to the living African fauna, and mammals which consist of *Elephas*, cf. *planifrons*, *Hippopotamus recki*, *H. protamphibius*, *Ceratotherium simus*, *Equus*, cf. zebra, with Suidae and Bovidae. The fauna is an association of Tertiary elements, e.g. *Dinotherium*, *Stylohipparion* and *Sivatherium*, with others of early Pleistocene age, such as *Elephas*, *Equus*, giraffes and antelopes.

These beds, which are early Pleistocene, are probably equivalent to the Serengeti and Olduvai deposits which have several species in common, to the higher terraces of the Vaal basin (see p. 1116) and to the Constantine Plateau Beds of Morocco. Africa, therefore, in early Pleistocene time had a mammalian fauna which ranged throughout the length and breadth of the continent. By the end of this time, the older element had disappeared. Eurasian forms entered in the middle Pleistocene but did not extend southwards across the Sahara.

Indian succession. In India,[631] two Pliocene mammalian faunas may be distinguished. In the earlier or Tatrot fauna, *Stegodon* (*S. clifti* and *S. bombifrons*) predominated over *Mastodon* (*M. sivalensis*) and occurs with *Hipparion* and abundant *Hippopotamus*. In the later Pinjor fauna, the first elephant, *Elephas planifrons*, appears but *Stegodon* and *Hippopotamus* still continue. These forms are followed by the Boulder Conglomerate fauna of lower Pleistocene age which includes the last *Stegodon* (*S. ganesa*) and *Elephas hysudricus*. *Equus* replaces *Hipparion* and *Bos* and *Buffelus* replace extinct genera of oxen and buffaloes. The following correlation seems justified:

Karnul Cave deposits and Trichinopoly Alluvium	Upper Pleistocene.
Narbada Boulder Conglomerate	Middle Pleistocene.
Pinjor	Lower Pleistocene.
Tatrot	Upper Pliocene.

The Chinese mammalian succession has already been described (see p. 545). Three main faunas can be distinguished.[632] The oldest, which contains *Equus*, *Paracamelus*, *Stegodon*, *Elephas*, *Epimachairodus*, *Eucladocerus*, bighorn sheep and rodents, is of Villafranchian age. The succeeding

fauna, which is associated with caves and fissures, is the "Sinanthropus" or Choukoutien fauna. The highest or Malan fauna is that of the upper Pleistocene loess.

4. Other vertebrates

Fish, batrachians, reptiles and birds were depicted by palaeolithic man (see p. 856) and their remains are found in cave and other deposits and in interglacial accumulations, e.g. the Cromer Forest Bed (see p. 995). Nevertheless, the remains are relatively rare; this is illustrated by lists of Pleistocene fish and birds from Great Britain and of birds from Mixnitz (see p. 791). During the cold epochs these vertebrates were displaced equatorwards (see pp. 1031, 1069, 1094) and were racially altered (see pp. 1378, 1096, 1378). Distributions were also modified in lower latitudes (see pp. 1113, 1123), where differentiation occurred (see p. 1116), and were affected by changes in the distribution of land and water (see pp. 1234, 1235, 1239, 1356). The migrations of fish and birds were considerably altered (see pp. 1400–1402). The final disappearance of the ice and the re-warming of the lands and seas brought about further migrations (see pp. 1290, 1296, 1311).

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CHAPTER XXXV

EARLY MAN

Historical. The literature dealing with early man is immense; it has been summarised in many works[1] of a general, archaeological or geological character. The purpose of this chapter is not so much to consider anatomical minutiae or the typology of the artefacts, which are strictly outside our province and can be studied in standard anatomical and archaeological works, but to prepare the ground for the next four chapters which deal with man's relation to the glacial and mammalian successions, to tectonic and climatic history and to the ecological environment. No attempt has been made to document this chapter fully.

If it be true that palaeoliths may be used as fossils with which to date geological horizons it is equally true that a geological foundation or background is vital in researches on palaeolithic man; early students of the latter, such as P. Tournal, E. Dumas, E. Lartet, P. C. Schmerling, J. Prestwich and C. Lyell, were all geologists.

In earlier days, largely because of Cuvier's influence, the existence of fossil man was denied—*l'homme fossile n'existe pas*. The implements, found in Pleistocene gravels, e.g. at Grays Inn Lane, London in 1690 and at Hoxne, Suffolk in 1800,[2] and in cave-breccias, rock-shelters, the "head" of south England or the loess, were deemed to be aberrant forms of fossil fish or the product of some chemical agency, of violent and continued gyratory water-action, or of fracture resulting from changes of temperature. Early geologists, indeed, like Buckland,[3] were unwilling to believe that extinct animals and man were coeval—even Lyell[4] only withdrew his opposition in 1859. Yet the antiquity of palaeolithic man was established in several ways. He inhabited caves which were of great age, as is proved by the thick stalagmite layers, by changes in the relief and drainage systems, and by the sequence of contemporary events elsewhere. He coexisted with extinct Pleistocene mammals; for, as J. F. Esper recognised as early as 1771, bones of man and cave bear are found together, his implements occur with their bones and teeth; he made paintings, drawings and engravings of them in Spanish and Pyrenean caves and marked their bones, e.g. rhinoceros bones in Bohemia,[5] and sometimes polished them (though polishing does not necessarily imply a human origin[6]), and his footprints are preserved from Magdalenian time.[7] The human succession can be related to changes in the animal and vegetable world, to river and marine terraces, to glacial successions and to loess horizons, etc.

Cumulative evidence carried conviction to the most sceptical. Implements were discovered with bones of extinct animals[8] in Kent's Cavern, Brixham Cave, Wookey Hole and caves of Aurignac, and in river-gravels[9] in the Somme and Thames and of Austria; and human and animal bones were found together in a number of French Caves,[10] including the Engis. Doubts, however, were only finally allayed by Rigollot's verification (1855) at St. Acheul[11] of Boucher's finds[12] in the Somme valley which were recognised by British archaeologists and geologists[13] who visited Abbeville and Amiens in the year (1859) that Darwin published his *Origin of Species*. More recent

finds of calcined bones of mammoth and rhinoceros, e.g. at Kesslerloch,[14] of mural paintings and drawings of the animals[15] (see p. 856) and of plastic representations of the mammoth at Pollau in south Bohemia[16] only confirm these conclusions.

Lucretius (died 55 B.C.) and independently Aldrovandi (1522–1607), Mercati (1544–93) and J. G. Eckart (in 1750) expressed the opinion that man passed through the successive stages of stone, bronze and iron.[17] It was, however, only in 1836 that confirmation of the three ages was obtained when C. J. Thomsen[18] of Denmark, aided by G. Forchhammer, S. Nilsson, J. J. A. Worsaae and others,[19] placed on a sound basis this threefold chronology, the "basis of prehistory" and the "corner-stone of modern archaeology". Worsaae,[20] on stratigraphical grounds, related the three ages to the tree succession (see p. 1438) and later subdivided the stages, distinguishing two stone ages, two bronze ages and three iron ages. The two divisions of stone implements, the early flaked, the later polished, first recognised in France, J. Lubbock[21] termed respectively palaeolithic and neolithic.

1. *Pre-Palaeolithic Man*

Eoliths. Eoliths were first discovered in 1867 in the upper Oligocene near Thenay, south of Orleans,[22] though the name "dawn-stone" (*eos*, dawn; *lithos*, stone) was not given until more than twenty years later.[23] In 1877 the eoliths were found in the upper Miocene of Puy Courny, Auvergne,[24] and since that time have been discovered on many other horizons (see below; fig. 158).

Their origin has given rise to prolonged controversy.[25] One difficulty is to distinguish between art and nature, between man's workmanship and the simulation of his artefacts by natural causes. The marks of design are equivocal, and our knowledge of the actual processes and results of natural flaking is incomplete. No infallible means of distinction is yet known. Believers in eoliths regard as human the bulb of percussion, the pointed ends, the curvilinear notches, the "resolved flakes" and the marginal retouches. Moir,[26] who discussed their mode of manufacture, thought the distinction lay in the angle at which the flakes were removed. They are characterised by one-sided flaking[27] or have a dome or crusted top, a flat and naturally fractured base, and a steep edge-flaking made by blows delivered around the under surface.[28]

Eoliths have now been described from Britain[29] (Kent, Hertfordshire, Wiltshire, Sussex, Hampshire, Essex, Berkshire, Dorset, Norfolk, Suffolk, Surrey), France[30] (Loire, Oise, Somme) and Germany,[31] as well as from countries remote from Europe, e.g. Burma[32] and central Australia.[33] They are extracted from the Eocene,[34] e.g. its base at Belle-Assise in the Paris Basin and the Thanet Sands of England; from the Oligocene,[35] e.g. at Boncelles near Liège and Thenay (Loir-et-Cher); from the Miocene[36] of Puy Courny (Cantal) and Otta (Portugal); from the Pliocene[37] of St. Prest, Dewlish in Dorset (= Pleistocene[38]), Suffolk Crag, Thebes (Egypt) and of Russia; from the Cromer Forest Bed[39] and glacial drifts[40] in Britain and Germany; and from "postglacial" beds[41] in Rügen and Bornholm, and beds of late prehistoric date in England.[42] A Rutot distinguished the following phases in the Tertiary: 1. Thanetian (lower Eocene); 2. Fagnian (middle Oligocene); 3. Thenayan (upper Oligocene); 4. Cantalian (upper Miocene); 5. Kentian

(middle Pliocene); 6. Saint Prestian (upper Pliocene). His later Mafflian, Mesvinian and Strépyian he himself recognised as equivalents of the lower palaeolithic facies.

While some deem the eoliths to be a primitive type of no special age which

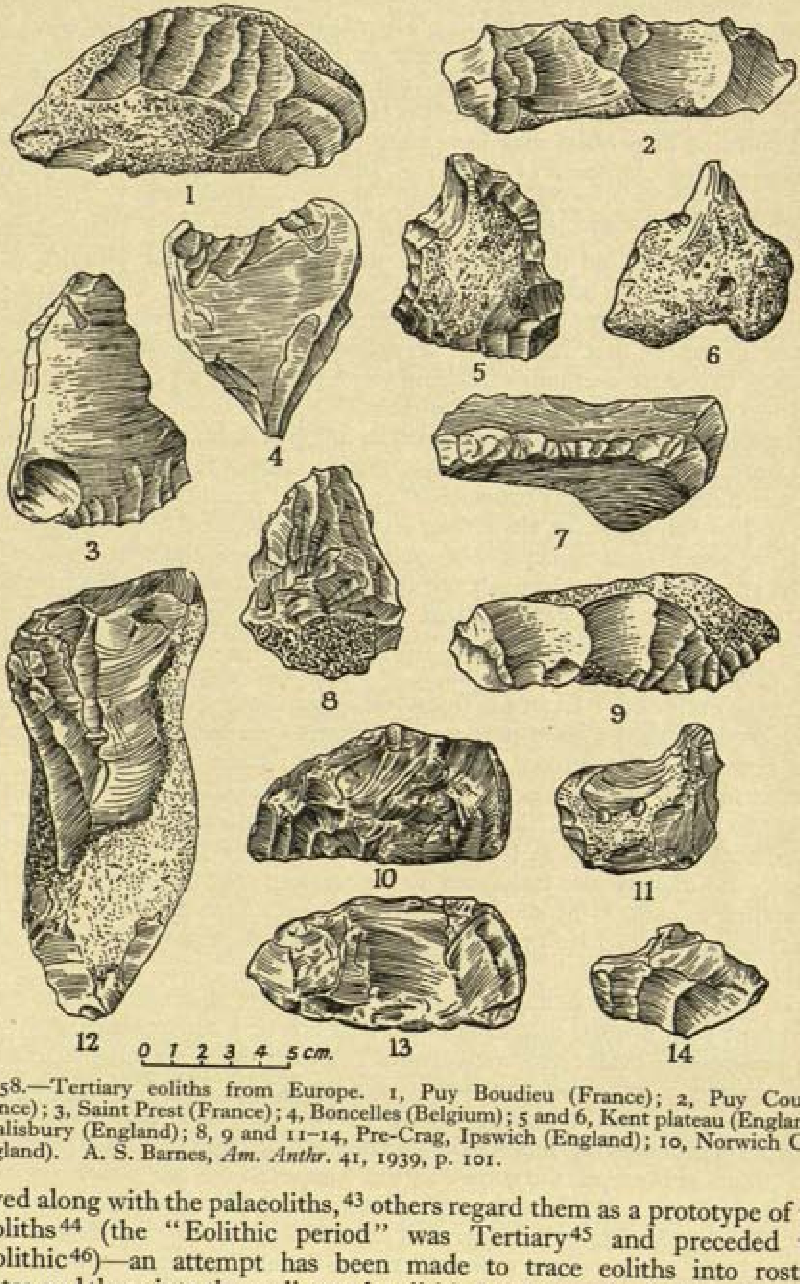

FIG. 158.—Tertiary eoliths from Europe. 1, Puy Boudieu (France); 2, Puy Courny (France); 3, Saint Prest (France); 4, Boncelles (Belgium); 5 and 6, Kent plateau (England); 7, Salisbury (England); 8, 9 and 11–14, Pre-Crag, Ipswich (England); 10, Norwich Crag (England). A. S. Barnes, *Am. Anthr.* 41, 1939, p. 101.

survived along with the palaeoliths,[43] others regard them as a prototype of the palaeoliths[44] (the "Eolithic period" was Tertiary[45] and preceded the Palaeolithic[46])—an attempt has been made to trace eoliths into rostro-carinates and these into the earliest palaeolithic hand-axes.[47] Certain Tertiary eoliths of Spain have been proved to be true Pleistocene palaeoliths.[48]

The human origin, often affirmed,[49] is denied or regarded as "not proven"

by numerous British and continental workers.[50] While admitting that palaeoliths may not represent the infancy of stone-culture (eoliths were themselves preceded by still earlier but as yet imaginary "pre-eoliths"[51]) they consider that this stage may have developed elsewhere; that the forms did not become dominant until a certain excellence had been attained; and that the earliest stage was probably alithic. The earliest primitive implements were probably of impermanent wood, teeth or bone, or were claws, shells and natural flakes or pebbles, picked up from the surface as the pebble-culture of Kenya and Uganda and the Vaal river basin and Nile valley[52] may indicate —the splitting of pebbles may have been the natural precursor of the flaking process—or the choppers of Asia, e.g. India (Soan), China (Choukoutien), Burma (Anyathian), Malay (Tampan), Java (Patiitan), which are pebbles coarsely chipped at the edge (see fig. 159, p. 840, and p. 841). In east Africa the earliest-known and most primitive tools are the Kafuan pebbles with a single edge flaked on one side. These were followed by the chopping tools of Olduvai, with edges flaked in two directions, which pass upwards into pointed choppers that have been regarded as the forerunners of the true bifaces. Primitive methods of flaking stone show that an eolith-stage in the evolution of stone implements is unlikely.[53]

Opponents of human eoliths contend as follows: natural implements of this kind were amply available[54]; eolithic flaking differs from human flaking[55] and was made by natural pressure,[56] i.e. by the weight of superincumbent beds and by soil pressure, since their surfaces are striated in the Kentian and sub-Crag eoliths and coincide with planes of least resistance in the material; eoliths are in immediate contact with small pieces formed by fracture[57] and have occasionally been derived from abraded or broken palaeoliths after the earlier patination[58]; and they are restricted to flint gravels and are absent from clays, loess, travertines, peats or other fine deposits where pressure effects are excluded. Even the finest secondary flaking, the notches, parallel chipped edges, the bulbs of percussion (which G. de Mortillet regarded as the main criterion of intentional working) are only natural products.

Other forces[59] which mechanically give rise to eoliths are ice-floes and ice-sheets; foundering drifts; insolation, as on the plateaux of central Asia; or movements in beds, e.g. at the base of the Eocene in the London and Paris basins. Eoliths are also fashioned by the random concussion from sea-waves or swirling streams,[60] by the feet[61] of camels or other animals (podoliths), or by vehicles, and can be produced artificially by experiment[62] or by chalk-crushing machines.[63]

The finding of eoliths not in definite stations but in regions of flints is inconsistent with human origin, as is the absence of a recognisable purpose or of a progressive evolution[64] (successive "industries"[65] have been described from Belgium, Brunswick and south-east England). Their rigid unchangeability from the lowest Tertiary to the present and their constant repetition of form suggest natural causes which do not vary in their operation. Furthermore, flints grade from the rudest natural shapes to the few which are singled out as artefacts. These *hyperselectionées*, as Boule named them, are the exceptional types which must occur if an unlimited number of flints, the bulk of which are admittedly accidental, be examined. Finally, eoliths are too abundant, are unassociated with any other testimony of human occupation, such as hearths, burnt bones or osteological remains, and they are improbable on palaeontological and evolutionary grounds[66] (see below).

Notwithstanding the cogency of some of these reasonings, it may be that natural forces are incapable of simulating eoliths and that these occur at different horizons or where natural processes can be excluded, e.g. where bivalve shells, still hinged, are found in the immediately overlying layer.[67] The issue of the battle of eoliths is still undecided: it awaits fresh evidence of some decisive kind, such as an undoubted hearth or occupation-floor or skeletal remains, which will convert presumption into proof.

Rostro-carinates. The Stone Bed of Norfolk (= Nodular Bed, Detritus Bed or Suffolk Bone Bed), about 1 ft (*c.* 30 cm) thick, lies at the base of the Red Crag at Ipswich and from Norwich to Guist in the west and Weybourne in the north. It represents the spreading of the unfloatable debris of the Tertiary land-surface by the advancing Crag sea. Resting on the Chalk, it consists almost wholly of grey-black flint of the Upper Chalk, with occasional quartz or quartzite, sporadic fossil bones and, in places, typical Crag shells. The bed has yielded awls, scrapers, a few hand-axes and abundant flaked implements,[68] in either disturbed or undisturbed positions,[69] which E. R. Lankester[70] termed the "Icenian industry", but are perhaps preferably denoted[71] Ipswichian (from the Red Crag at Ipswich) and Norvician (from the base of the Norwich Crag)—"Icenian" has been used stratigraphically for the Norwich Crag (L. D. Stamp) or for the Norwich Crag, Chillesford Beds and Weybourne Crag (F. W. Harmer). The implements, which are of a rich mahogany colour and sometimes striated (possibly by solifluxion or by a subsequent glaciation[72]), have been shaped from nodules on a definite plan[73] and resemble the prow of an upturned boat. These "rostro-carinate" ("beaked" and "keeled") implements seem to be crude attempts to produce points and edges, using flint nodules as a starting point. Because of their edge-chipping and surface-flaking they have been placed midway between eoliths and palaeoliths and in advance of the Kentian eoliths,[74] alternatively in the direct ancestry of the more elaborate Chellean.[75]

It has recently been affirmed[76] that the Bone Bed, which is a residual deposit representing the wreckage of many ancient land-surfaces, contains artefacts which can be divided by (*a*) patination and reflaking, (*b*) types, (*c*) differences in technique and (*d*) condition, into five groups of which the rostro-carinates form one.

Although archaeological opinion is inclined to accept the authenticity of these industries[77] (the resemblance in the fashion of flaking and repetition of form are strong arguments), other writers[78] deem the rostro-carinate to be natural and see in the striations and the gradational series proofs of their mechanical origin. The numbers on a given site are immense; they occur on modern beaches,[79] in a *cimentière* at Beaumont-sur-Oise[80] and as projections from a big flint boulder[81]; the patination of the various facets varies[82]; they are apparently purposeless (though it has been suggested that they were used for removing the hide from an animal[83]); and they are found at different horizons as in the Eocene,[84] Cromerian,[85] Middle Glacial Sands and Gravels,[86] Chalky Boulder-clay,[87] postglacial deposits,[88] e.g. at Ballymena and in the Larne raised-beach, and from unknown horizons in Egypt,[89] Rhodesia,[90] Uganda and the Victoria Falls region[91] (Kalahari Sands) Olduvai[92] and Japan.[93]

Whether or not the implements, if authentic, prove the existence of Pliocene man depends in turn upon whether the Norwich Crag is to be regarded as Pliocene—the long-established practice—or placed in the lower Pleistocene[94]

(see p. 599). Tertiary man in west Europe has no other confirmation. The so-called elephant trench at Dewlish[95] (see p. 832) in Dorset is natural[96]; the figure-stones (*pierres-figures*), accepted by many[97] since B. de Perthes[98] first described them, are of doubtful antiquity[99]—the "artificial" incisions on animal bones[100] may be due to gnawing animals or to earth-pressures and may be no more authentic than the model of a mammoth discovered in Suffolk[101] or the human footprints in Pliocene Beds.[102] Nevertheless, such evidence is sought in the bone implements below the Crag,[103] a slingstone (near Ipswich[104]) and perforated shark's teeth beneath the Red Crag,[105] a humanly shaped piece of wood from the Cromer Forest Bed,[106] burnt flints[107] and alleged human remains,[108] including the jaw of "Foxhall man"[109] which like other skeletal remains attributed to Tertiary man (including those of Savone and Castenedolo in Italy, and of Calaveras in California) has not withstood the test of critical enquiry.

Many think Tertiary man is required for the development of the human brain of earliest Pleistocene man.[110] Others regard man in the narrower specific and broader generic sense as essentially a product of Pleistocene climatic changes which provided the cause and the opportunity of his appearance.[111]

Unfortunately, the palaeontology of the Primates is only very incompletely known.[112] The earliest fossil Primates, the relatives of the lemurs and tarsiers, are found in considerable numbers in the Eocene of Europe and America. The lower Oligocene of the Egyptian Fayûm contains *Parapithecus* which was connected with the tarsiers and the anthropoids and has been variously regarded as a primitive Old World monkey, as a primitive anthropoid ape, or as a proto-catarrhine from which all living catarrhine primitives have been derived. It also contains *Propliopthecus*, a small and generalised anthropoid. Among the fossil Old World apes this may be the most nearly related to the common stock whence sprang the four types of higher apes and man. Of these the gibbon stands somewhat apart, while the gorilla and chimpanzee have diverged in some respects from their remote ancestors which they shared with man. Early gibbons and forms intermediate between the chimpanzee and gorilla have been discovered in the Miocene of Europe, Asia and Africa, e.g. *Proconsul* of Africa, and fossil orangutans (Dryopithecinae) in the upper Miocene of the Siwalik Hills of India. Fossil evidence shows that at the beginning of the Miocene the main groups of the anthropoid apes which exist to-day were already undergoing separately their evolutionary definition. It also suggests that the ancestors of the Hominidae are to be sought in some branch of the early Miocene Dryopithecinae,[113] though a large Australo-pithecine ape and *Limnopithecus* of the Miocene of Kenya have been named as ancestors[114] and *Pondaungia* and *Amphipithecus* of the upper Eocene of Burma suggest caution in affirming an African ancestry of the anthropoid apes. During the Pliocene of the Old World, fossil anthropoid apes and almost all the present genera existed. Many species were ancestors of present species, the ancestors of the chimpanzee-gorilla group migrating westwards into Africa and the ancestors of the orang migrating eastwards—a fossil molar tooth has been found as far north as China.[115]

Man may have evolved contemporaneously in different regions[116] (see p. 863). This was maintained among others by D. Black[117] who discussed the modern and geological distributions of the Primates. The human family

probably descended from the anthropoid group in the Miocene and Pliocene somewhere between Western Europe and eastern Asia[118]: the centre of evolutionary radiation may be represented perhaps by the fossiliferous deposits of the Siwalik Hills.[119] Palaeontologically, there is no objection in principle to the existence of man in the late half of the Tertiary,[120] though there is no support for the idea of a separate existence of the human stock in earlier Tertiary times.

No valid reason, therefore, exists against the existence of some primitive Tertiary man. Nevertheless, he remains conjectural; no irrefutable evidence in the shape of perishable bones has been found in strata admittedly older than the Pleistocene.[121] Even if the artificial nature of the implements be established, legitimate doubts may still be entertained whether they were fabricated by beings fully human. The Tertiary seemingly had the progenitors of man but not man himself.

2. *Palaeolithic Man*

Materials of implements. Either because the wooden implements of palaeolithic man, especially lower palaeolithic man, have been subsequently destroyed or, less probably, because wood was absent from the Pleistocene tundras and steppes, virtually nothing made of this material is known until we come to the neolithic pile-dwellings. Exceptions are provided by a pointed stake from Clacton,[122] associated in peat with the remains of *Elephas antiquus*; a complete yew-wood spear from Lehringen near Bremen, also associated with a skeleton of *E. antiquus*[123]; certain objects found in the lower Palaeolithic in Alsace[124]; and fossil wood used in the Early Anyathian culture (early Pleistocene) of Upper Burma.[125] One of the skeletons of *Palaeanthropus palestinensis* found in a cave on Mount Carmel had a clean-cut hole passing through the head of the femur into the pelvis, a plaster cast of the hole reproducing the tip of a wooden spear of which no other trace remained.[126] The making of fairly large wooden objects, such as food vessels and shields, probably played a large part in the industrial tradition of the Aurignacian peoples of the Near East. Their weapons were also probably made of wood.[127]

The palaeolithic implements which have come down to us are therefore made of stone, chiefly flint, less commonly, as in Gower, south Wales, of chert.[128] The flint was gathered from Tertiary gravels and marine shingle and broken on anvil-stones[129] or was mined directly from the Chalk, e.g. at Grimes Graves[130] (the most extensive of the prehistoric flint-making shafts in England), which was worked chiefly to provide the axes to clear the mixed oak forests of Breckland. Animal engravings upon flint crust and the form of the implements, notwithstanding the absence of a Pleistocene fauna and the presence of pottery,[131] have led some archaeologists to refer the beginnings of the excavations at Grimes Graves to palaeolithic time.[132] Grimes Graves workings, however, are no longer accepted as palaeolithic but are regarded as either early Mesolithic[133] or Neolithic.[134] Flint mining, indeed, attained its peak in the late-neolithic and early Bronze Age[135] and was widely practised in west Europe from England to Portugal.[136] The flint found widespread use because it fractured easily and was abundant, hard and imperishable. Where there was none, it was probably introduced, as in south Germany[137] (worked from Chalk subsequently eroded?[138]) or Campbeltown, Kintyre.[139]

Other materials were used relatively rarely though a lengthy list has been compiled for Europe.[140] They included jasper and radiolarian chert of the Alpine Jurassic, chalcedony of the German Keuper and of Northern Rhodesia,[141] felsite,[142] Hertfordshire puddingstone,[143] quartzite, e.g. in the Chinese loess,[144] in the Aurignacian of Moravia,[145] in Northern Rhodesia,[146] at Brandon, Creswell Cave, Drachenhöhle,[147] and in the "quartzite province" of Brittany and the Garonne and the Grotte de l'Observatoire, Monaco[148] (where, as in North Africa, quartzite implements preceded flint ones[149]). Other rocks included basalt, e.g. in Auvergne, obsidian, serpentine, jade, clay slate, limestone, e.g. in the Drachenloch, in Torralba, at Monaco[150] and in a few Mousterian stations in central Europe,[151] and quartz, chalcedony and lydianite in South Africa.[152] Teeth of animals, e.g. of bear at Drachenhöhle,[153] were also used, as were bone and horn in the lower Palaeolithic[154] and especially in the upper Palaeolithic when reindeer were plentiful. A shaped bone (horse) of lower palaeolithic age has been found at Warren Hill, Suffolk.[155] Excavations in the Dordogne by E. Lartet and H. Christy (1865) showed that bone, ivory and deer's horn played a large part in the industrial activities of later palaeolithic man. The advanced technique, however, must have been far removed from the first utilisation of bone and ancient prototypes. A few examples are known from the upper Mousterian of Castillo (Spain) and La Quina (France) as well as the anvil blocks and trimming tools of the same age—the bone said to have been worked by "Piltdown man" (see p. 859) was apparently made by *Trogontherium*.[156] Bone splinters, jaws and other bones of great bear were used,[157] e.g. in the "alpine Palaeolithic" (see p. 1035), where they served for treating the skins of cave bear. Stag horns were readily obtained and shoulder-blades were employed as shovels.[158]

Excavations in the loess at Předmost[159] have revealed a unique series of cultural objects of upper palaeolithic age, viz. spades and forks of mammoth bone, horn "buckles", daggers made of the small bones of the legs of lions, needles of reindeer horn, assegais and daggers used in hunting, and perforated mammoth ribs with pieces of polished bone inserted in the perforations.

The raw material used by palaeolithic man in Burma was silicified tuff and fossil wood[160] and in China, quartz, quartzite, quartz-porphyry and sandstone.[161]

Patination of flint. Acids in rainwater dissolve from the surface of the flint the more soluble constituents, the opaline silica. The porous meshwork that is left scatters the light so that the surface appears white, or in the earlier stage blue. Once the surface is made porous, it absorbs mineral salts from the soil and becomes patinated. Flint implements are patinated in various colours. The patina or thin skin of chemically weathered flint may be opaque dead white, red, brown, yellow, ochreous, green or black, and may have a slight polish or gloss identical with "desert varnish". Flints in the same gravels generally agree in the colour of their patina; reworked implements are usually doubly patinated. The colour change, which varies with the composition and primary condition of the flint, the degree of exposure, and the matrix enclosing the implements, is due to alteration, the deepest patination often denoting greatest age.[162] Patination may occur before burial[163] by physico-chemical processes induced by the sun's rays, etc., but more commonly by staining while the flint is in the gravels. The white patina of some gun flints or flints in abandoned quarries suggests that the

change may take place rapidly. Patination as a guide to the age of a deposit may therefore be dangerously misleading.[164]

Patination, occasionally studied,[165] has been produced by experiments[166] which suggest that the chemical agents are the carbonates of potash, soda and ammonia which work more quickly on rubbed or polished implements than on chipped ones. The first step is the removal in solution of part of the film and interstices which consists of opal (colloidal silica) from the more sponge-like meshwork of chalcedony (crystalline silica) whose minute air-spaces render it porous and white.[167] The patina or extremely thin impervious skin of the altered crust is formed when evaporation concentrates the solution of silica at the surface. Blue is the incipient patina in which the white weathered material is drawn over the background of dark flint; red, orange or yellow patinas are due to staining of the white patina by ferric oxide or hydroxide deposited in the pores of the skin and derived possibly from iron originally in the interior of the implements.[168] Mottled patination is incipient and denoted by spots or ramifying streaks of different colour.

Cultural succession. Palaeolithic implements clearly reveal design. Rude fractures or "rejects" are found in "palaeolithic floors", i.e. the factories or working sites on which the flint workers lived and accumulated their innumerable flakes, cores, "rough-outs" and hammer-stones. First discovered in 1878,[169] the floors have since been described from many localities in the London Basin[170]: numerous replacements have been made as at Caddington.[171]

French archaeologists, like Boucher de Perthes[172] (1847) and E. Lartet[173] (1864), were the first to recognise the superposition of distinct cultures, each with its particular style of manufacture and finish and technical improvement over the one that went before it: Lartet based his classification on zoological and palaeontological grounds (see p. 815). The early division into River Drift man and Cave man was faulty and misleading since river-drift types also occurred in caves and *vice versa*, as Sir J. Evans[174] recognised (though even to-day few caves among the hundreds of Pleistocene caves known contain remains older than the Riss glaciation). G. de Mortillet's classification[175] which replaced it substituted for Lartet's palaeontological titles archaeological ones based on type-sites. His classification, which recognised periods of time and not cultures, was imperfect in that it did not appreciate the true position of the Aurignacian which H. Breuil,[176] returning to E. T. Hamy's affirmation of 1870,[177] subsequently established as at the base of the upper Palaeolithic. This amended classification, which investigations by E. Cartailhac,[178] L. Capitan and D. Peyrony[179] placed on a firm basis, was formally approved at the Monaco Archaeological Congress[180] (1906). Later research has refined the divisions, added sub-stages and shown that their succession is not straightforward (see below).

The "classical" sequence was found to hold outside France, as in Belgium[181] (A. Rutot's Moséen, Campignien, Hesbayen and Flandrien) Germany[182] (see below), north Spain,[183] south Tunisia[184] and Russia[185] but was thought to be inapplicable to England[186] until correlations attempted in the early years of this century[187] and later successfully applied in Kent[188] established its correctness for that country. Doubt, however, may be expressed whether it can be used outside Europe where implements, undoubtedly palaeolithic, are widespread.[189] Investigators have affixed labels to the palaeolithic cultures which properly belong to west European cultures and

are probably misapplied when affixed in this way, unless it is understood that their use does not imply anything as to the age of the tools or the identity of their makers. It is indeed dangerous to extend these cultures across whole continents.[190] For example, the whole prehistoric complex in Uganda is different from that in Kenya-Tanganyika in its environment and raw materials, and close correlation of the cultural stages of the two regions is not possible.[191] In Burma[192] the cultures differ in several fundamental respects from those of west Europe and have therefore been given a new name, the Anyathian (after the colloquial Burmese for an Upper Burman), subdivided into different stages. Nevertheless, unlike the Far East which is devoid of the

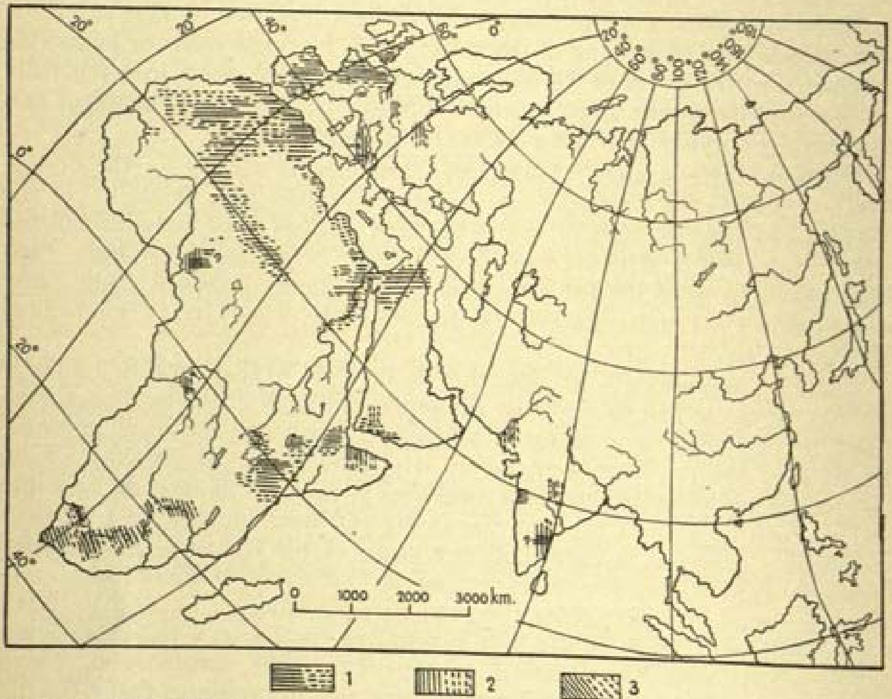

FIG. 159.—Broad distribution of lower palaeolithic cultures in the Old World. 1, primitive and evolved; 2, evolved; 3, Stellenbosch and Fauresmith. S. A. Huzayyin, *842*, pl. I.

various lower and middle palaeolithic assemblages of the west, the Near East, Russian Turkestan and Peninsular India have a developmental sequence closely paralleling that of Europe during middle palaeolithic times.

Classification based on typology alone is liable to be unsound. Caution is required in recognising the work of the master and the apprentice and dis-tinguishing between intentional and accidental and finished and unfinished stages. Confusion is introduced by intermixture owing to soil creep, trail, the action of roots and burrowing animals, or the "rebirth" of a type through later copying by a people who had no connexion with its creators.[193] It arises too from differences of opinion in classifying particular implements and the failure to perceive that the French succession may have only regional signifi-cance[194] on account of racial differentiation then as now. During the lower Palaeolithic, parts of Europe were simultaneously occupied by cultures

characterised by totally different industries. Makers of the "coup de poing" lived west of the Rhine (they hailed from Africa) while east of the river and as far as China there were flake industries. The French industries, for example, cannot be applied without modification to Italy[195] nor to Germany according to Wiegers[196] who has proposed for this country a new but in the opinion of most authorities unnecessary classification: Halberstadt stage (Chellean), Hundisberg (lower Acheulian), Markkleeberg (upper Acheulian), Weimar (lower Mousterian), Sirgenstein (upper Mousterian), Willendorf (Aurignacian), Předmost (Solutrean), Thaing (Magdalenian) and Ofnet (Azilian).

That a cultural succession existed is now overwhelmingly proved. Yet different cultures may be partly contemporaneous just as to-day the primitive Tasmanians and the Fijians, who make polished stone implements, are still in a stone age.[197] Nevertheless it is becoming increasingly clear that archaeology is dealing with a sequence of cultures and not of cultural epochs, each culture having a spatial as well as temporal significance.

H. Breuil[198] and H. Obermaier[199] have gradually approached the idea of two great currents of civilisation, the flake-cultures, largely Asian and distributed from China westwards to east and central Europe, and the hand-axe or biface cultures, largely Eurafrican, and in Europe west of the Rhine. These cultural streams do not run parallel and independently: they are perpetually meeting and influencing each other and even merging to produce new facies. Nevertheless, they may be used for correlation purposes since the succession has nowhere yet been seen in reverse order. Breuil divides the older Palaeolithic as follows:

Flake Industries (*cold climate*)	*Hand-axe Industries* (*warm climate*)
Mousterian	
	Micoquean
Levalloisian	
	Acheulian
Clactonian	
	Chellean or Abbevillean
Ipswichian	

Significantly, the hand-axe cultures, which are particularly well fitted for dealing with trees, wood or roots, belong to interglacial phases and the flake industries to the cold climates and the hunter's life of the glacial epochs. Broadly speaking, the flake-tool cultures are found from the North Sea to China and those of the core-tool are restricted to Africa and western Europe—they have in recent years been found east of the Rhine,[200] e.g. at Hannover, Petersdorf, lower Saxony and Předmost. There were, therefore, during lower palaeolithic time at least two distinct cultural cycles each made up of a greater or smaller number of differing though allied cultures. While this differentiation into parallel phylla may be true for west Europe, it is seemingly not so for the rest of the Old World[201]; for flakes and bifaces occur together throughout Africa, e.g. in Egypt, Belgian Congo and the Rhodesias, and in India. Future discoveries will certainly make necessary extensive revisions of our present schemes. The upper Palaeolithic saw the addition of a third cultural element, the blade and burin industry, which had an immensely wide distribution.

Men at the *Pithecanthropus-Sinanthropus* stage of physical evolution extended seemingly down east Asia from Peking to Java and westwards to north

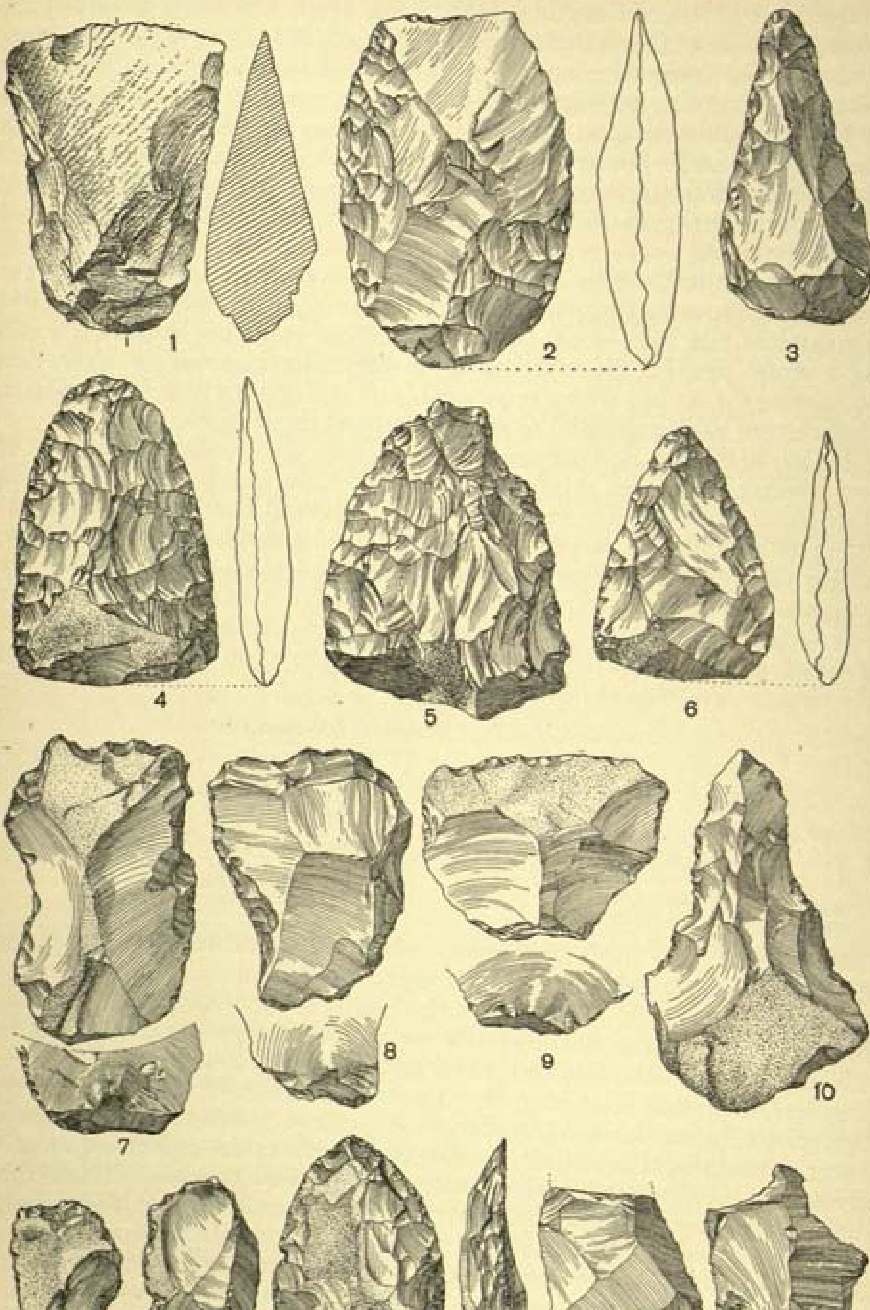

Fig. 160

India and to East Africa: they had a culture of chopping tools,[202] e.g. in North China, Burma, Java, Malaya, and north-west India.

Pre-Chellean. The earliest stage in the evolution of the great and widespread culture of the hand-axe or "coup de poing" is the Pre-Chellean of the early French archaeologists[203] ("Proto-Chellean"[204]). Indefinite as to both its age and its form, it represents the lowest stage of positively recognisable human implements or, in the opinion of those who accept eoliths, a transition to true palaeoliths. The maker was not designing an implement but seeking by a few blows to fashion a sharp point or cutting edge.[205] Such implements have been discovered in the Somme, in the Cromer Forest Bed, in Belgium (Rutot's Strépyian[206]) and at Swanscombe, Clacton and Torralba.

Abbevillean (Chellean). The Chellean implements, named after Chelles,[207] Seine-et-Marne, have been rechristened Abbevillean by Breuil[208] since practically all the tools at the type station being to the Acheulian culture. The tools, which were worked on both faces, generally by a hard hammerstone or on a fixed stone anvil, are more or less pear shaped with deep biting flake-scars and a fair proportion of the original crust or cortex retained on or near the butt. These core tools were dressed by coarse flaking to form a wavy edge along the median line. Fitted to the hand or used as wedges they served the purpose of axe, saw or chisel.[209] They were used mainly for cutting and scraping and probably for skinning game. Well-defined scrapers supplemented them.

Abbevillean implements are widely distributed (fig. 161) and like the succeeding Acheulian entered Europe from Africa and the Mediterranean; they are found in Italy[210] and spread through France to Kent's Cavern in south England but are absent from central and eastern Europe,[211] north of the Black Sea and Caspian Sea, and from Palestine. It has been thought that they may have evolved from the core and flake industries of the Crags.[212]

Human remains of Chellean man are rare, for unlike Neanderthal man who largely dwelt in caves (see p. 1032), Chellean man lived in the open. They may include, however, the Mauer jaw,[213] teeth at Taubach,[214] the Ehringsdorf jaw[215] and (most doubtfully) the Galley Hill skull[216] (cf. pp. 857, 859).

Acheulian. Acheulian implements (type station, St. Acheul, Somme[217]), developed from the Chellean, include the hand-axe which is still characteristic though usually smaller and lighter than the previous type as well as flatter and thinner and sharp-edged all or nearly all the way round. This axe with its pointed or rounded end is accompanied by the "cleaver" which has a straight and sharp cutting edge. The workmanship is finer and more elegant —the flake-scars are shallower—due to the discovery of the "wood technique", i.e. the use of softer striking material, ultimately a bar of wood or bone, antler or soft hammerstone. The flakes are less coarse and the edge is

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FIG. 160.—Early implements and hand-axes. *Brit. Mus. Guide*, "Flints", 1950, pl. I.

1, cleaver, Oldovai, Tanganyika Territory; 2, cleaver, Bournemouth district, Hampshire; 3, Acheulian pointed hand-axe of late Micoquean type, Yiewsley, Middlesex; 4, Late Acheulian cordate hand-axe, Bournemouth, Hampshire; 5, cordiform hand-axe of Levallois culture, Baker's Hole, Northfleet, Kent; 6, hand-axe of Mousterian culture, Le Moustier, Dordogne; 7–9, Clactonian flakes, basal gravels of 100-ft terrace, Rixon's pit, Swanscombe, Kent; 10, Clactonian flake resembling a hand-axe, base of 100-ft gravels, Barnfield pit, Swanscombe, Kent; 11 and 12, Clactonian flakes, Jaywick, near Clacton, Essex; 13, highly finished tool made on Clactonian type flake, High Lodge Hill, Suffolk; 14 and 15, Acheulian flakes struck in manufacture of hand-axes, Rixon's pit and Barnfield pit, Swanscombe, Kent (all to 1/3 scale).

repeatedly retouched into an even and regular line to give a symmetrical shape. Scrapers were increasingly used, especially in upper Acheulian time, probably because of the increasing use of skins consequent upon climatic deterioration (see p. 1029).

As in the case of the previous Chellean the definition of the Acheulian has varied considerably. As originally defined by de Mortillet,[218] it applied to all the lower Palaeolithic (River-drift of Evans) though he subsequently renamed most of it Chellean. This tendency has recently been reversed and the Acheulian has been restricted at the expense of the Chellean which most probably arrived in Europe from Africa fully developed.[219] The changes in the meaning attached to the various names[220] make the literature of the different decades difficult to follow.

Several Acheulian traditions developed in Europe, Africa and Asia, their characteristics depending on the assemblages of forms of biface: some were made from large pebbles, some of flakes struck from virgin rock, some of flakes removed from prepared cores. Breuil, mainly on stratigraphical grounds, has divided the Acheulian of the north of France into seven sub-zones. Nevertheless these zones are extremely difficult to distinguish typologically: three stages only, namely, lower (I–II, Commont's Chellean), middle (III–IV) and Micoquean, are recognisable.[221]

The Acheulian is distributed over west Europe, especially in the French valleys of the Seine, Marne and Somme.[222] A separate culture province with quite dissimilar technique, possibly a precursor of the Levalloisian,[223] replaces the Acheulian in Belgium.[224] This is Rutot's Mesvinian,[225] named after Mesvin, near Mons. Acheulian also extends throughout Africa from North Africa and the Sahara to the Congo, East Africa (Kamasian and Kanjeran pluvials), the Zambesi and South Africa; and into Palestine, Syria, Arabia, Mesopotamia and India.

Micoquean. The biface industry of Micoque[226] is spread from England to southernmost France,[227] e.g. at the shelter of Micoque in the valley of Vézère, Dordogne, in the Somme, at Traveller's Rest, Cambridge, and at Wolvercote in the bottom of the buried valley of the Thames near Oxford. Its characteristic lanceolate hand-axes are thin in section and narrow pointed. An industry astonishingly close to this is found in Palestine and Syria.[228]

The Micoquean is mixed with the Middle Levalloisian (see below) or older Mousterian (Tayacian,[229] from Tayac, Dordogne; see below), and later with evolved Levalloisian or Mousterian proper, according to the region, that give the Combe Capelle type of cordiform and triangular hand-axes.

The Micoquean also spread into the Crimea, Caucasus and Palestine where it was intermediate in time between the Acheulian and Mousterian and so earlier than in Germany and south-east Europe.

Ipswichian. The Ipswichian, the first of the flake industries, has flakes of small size, with retouch and a striking platform which is irregular and variable. They lacked a definite plan.

Clactonian. The Clactonian of Breuil[230] (also "Brecklandian"), of unknown osteological connexions, marks an advance in technique from the Ipswichian. The typical flint implement is a stout side-scraper with a steep flaking angle, the plane of separation being markedly oblique (120° or so) to the simple striking platform. Experiments have shown how the flakes were made.[231] The beautiful retouch towards the end of the industry, as is found

for example in the brickearths at High Lodge, Mildenhall, Suffolk, seems to demand a wooden striker. The industry is based upon the type found at Stoke Newington and at Clacton in Essex[232] and at Northfleet, Kent.[233]

Like the other flake-industries of lower palaeolithic age it is geographically restricted.[234] Besides the places just mentioned, it is found in England at Hoxne, Foxhall Road (Ipswich), High Lodge (Clactonian III) and Warren Hill, Suffolk (formerly classed as Mousterian) and in the higher terraces of the Thames[235] (Reading, Swanscombe) and in France at St. Acheul, Abbeville and Monaco. In Belgium, it is represented by Rutot's Mesvinien (see above). Elsewhere, it is found at Santander and in central Germany[236] and in Africa,[237] both north and south, e.g. Morocco, Egypt, Sahara and Vaal

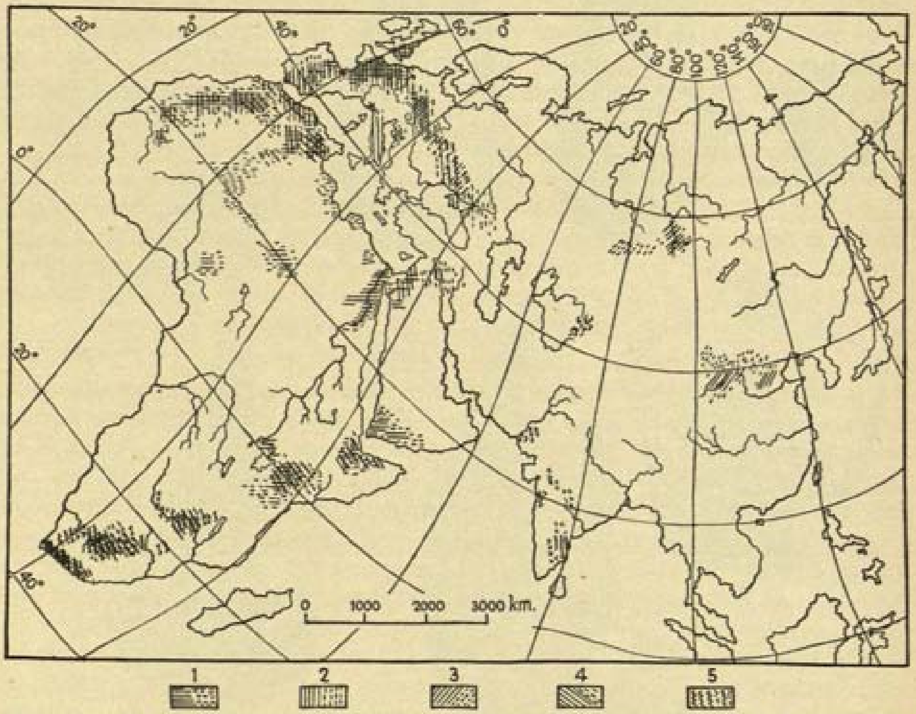

FIG. 161.—Broad distribution of middle palaeolithic flake-cultures. 1, Pure Levalloisian; 2, Mousterian, with or without Levalloisian tendencies; 3, flakes with Mousterian affinities in Eurasia; 4, evolved flake cultures in Africa; 5, other flake cultures. S. A. Huzayyin, *842*, pl. II.

River. The industry may be a modified survival of the early pebble-tool industries of Asia and Africa which spread into west Europe.[238]

The Clactonian in France is divisible into four stages (I–IV), the typological step between II and III being particularly big, possibly because of an absorption of Acheulian methods.[239] It had a variety in the Languedocian of H. Breuil[240] and evolved into Breuil's Tayacian,[241] an industry of small, coarse flake tools, found at Micoque, in Portugal and in Palestine and Syria, which was contemporaneous with the advanced Levalloisian of north France, England and Germany, the two industries reacting upon one another. Skeletal remains of the type of *Homo sapiens* have been found with Tayacian implements in Charente[242] (Fontéchevade).

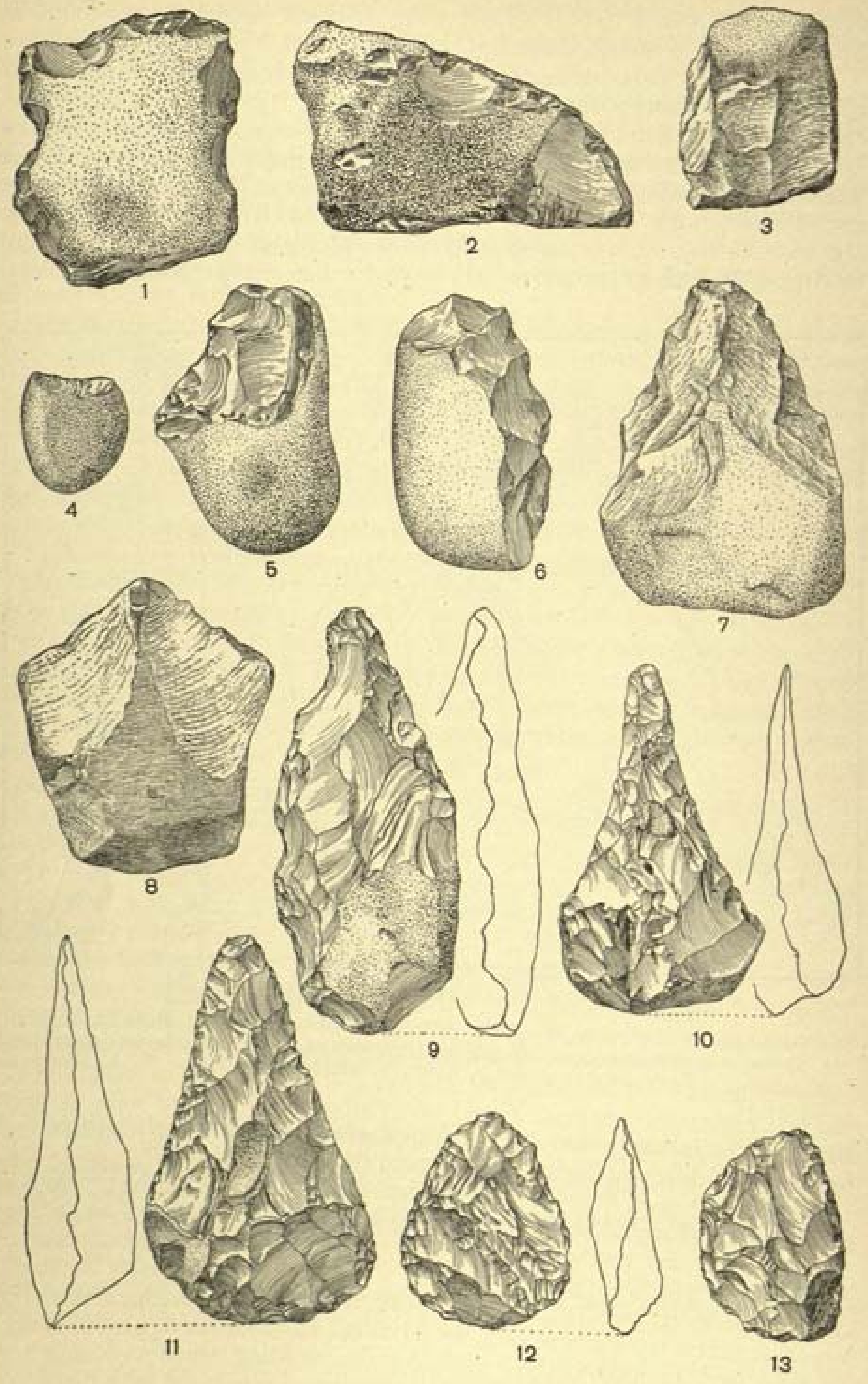

FIG. 162

Levalloisian. The Levalloisian of Breuil[243] is distinguished by its long, broad, thin flakes with conspicuous bulbs of percussion and carved edges, trimmed with secondary flaking and of finer workmanship than the Clactonian flakes. In this new technique a carefully prepared striking platform received the blow that separated the ready-made flake from the core and made the flat side. The plane of separation is nearly at right angles to the striking platform; Commont[244] described the mode of formation, which introduced the technique of the "tortoise core".

This industry, which coincided in its early stages with Acheulian IV and Clactonian III, was subdivided by stratigraphical means in the Somme valley into seven substages. It appears to have evolved from the Clactonian and may have originated in Germany whence it spread into France and later to England and Africa, especially into Cyrenaica, Tripoli, Egypt, Somaliland and the north-east generally—it has survived in South Africa practically into modern times[245]—and in Uganda, Poland and England to the end of the Pleistocene. Like the Chellean and the earlier Acheul stages it is found in the whole of western Asia including Anatolia, Arabia, Palestine and Syria.[246] Implements fashioned in the Levallois manner have been found associated with *Africanthropus* and Rhodesian man. Contact with the Mousterian led to the evolution of the Combe-Capelle and other subsidiary cultures.

In many African industries, e.g. the Victoria West and Fauresmith of South Africa, the Kalinian of the Belgian Congo (from Kalina near Leopoldville), the Nanyukian of Kenya (from Angata Nanyukie), the Sangoan of Uganda (from Sango Bay in Lake Victoria), the Levallois technique was used for the manufacture of late-Acheulian types of hand-axe.

Mousterian. The Mousterian (or Moustierian[247]), a name formerly used for all the palaeolithic flake-industries (other than the upper palaeolithic "blade industries"), including those which were later differentiated as Levalloisian or Clactonian, derives from the cave of Le Moustier, Vézère, Dordogne.[248] Its implements, more complex than the preceding ones, represent a flake industry of perfect technique derived from some extra European tradition or evolved directly from the Clactonian in Périgord[249] or by a fusion of Levalloisian, Tayacian and Acheulian elements[250]; the flint was worked on one side and then severed from the core, one side only requiring to be dressed to give a sharper edge. The sloping lateral retouch is typical. The implements also comprise a microlithic industry[251] and numerous side scrapers and points. The industry was far from being homogeneous: it embraced whole complex cultures or a number of localised industries or "phases" which make exact classification difficult.[252] There may indeed be no true Mousterian in England, the so-called Mousterian of this country being either Levalloisian or Clactonian III.[253] Strictly, Mousterian industries are those which it is considered were the handiwork of Neanderthal man.

FIG. 162.—Hand-axes and non-Levallois flakes. *Brit. Mus. Guide*, "Flints", 1950, pl. II. 1, colith, Kent; 2, rostocarinate, bone-bed below Shelly Crag, Ipswich; 3, pebble-tool, Olduvai, Tanganyika Territory; 4, pebble-tool, 10-ft terrace, Kafu River, Uganda; 5, pebble-tools, below the Crag, Bolton and Laughlin's pit, Ipswich; 6 and 7, pebble-tools, gravels, Lukasi River, Northern Rhodesia; 8, chopper, Konbyinmyint terrace, Thittabwe, Burma; 9, pointed hand-axe, Abbevillian type, Fordwich, Kent; 10, pointed hand-axe, Middle Acheulian *ficron* type, working floor, Round Green, Luton, Bedfordshire; 11, Middle-Acheulian pointed hand-axe, Milton Street, Swanscombe, Kent; 12, twisted ovate, valley of the Axe, Broom, Devon; 13, almond-shaped ovate, Milton Street, Swanscombe, Kent (all to 1/3 scale).

A bone industry of Mousterian age has been found in a number of places,[254] e.g. at Wildkirchli, Drachenloch, Wildenmannisloch, Petershöhle, La Quina, Castillo and Creswell.

The Mousterian, the middle Palaeolithic of some archaeologists,[255] was distributed over all Europe south of the ice-sheet[256] though not with equal intensity, the remains being least dense in France and Belgium, and near the northern limits of its territory and in mountainous districts, e.g. the Alps, Carpathians and Balkan Peninsula: it was absent from the Rhône basin and the French Riviera. It ranged from Jersey in the west, where skeletal

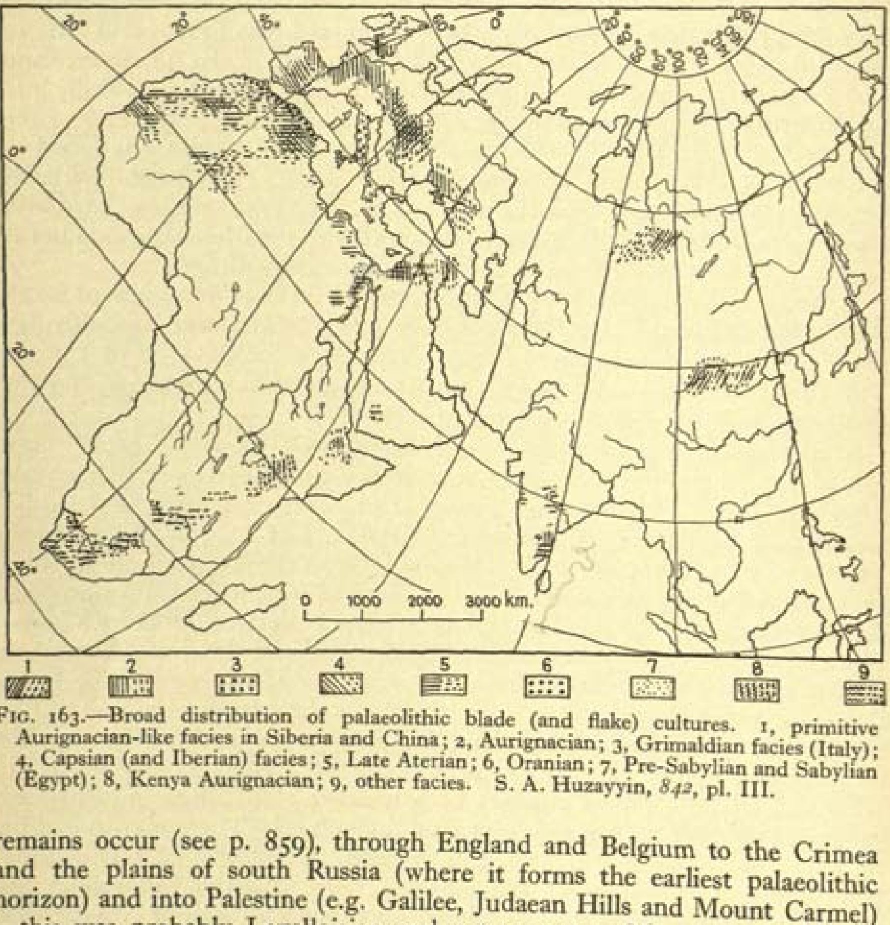

FIG. 163.—Broad distribution of palaeolithic blade (and flake) cultures. 1, primitive Aurignacian-like facies in Siberia and China; 2, Aurignacian; 3, Grimaldian facies (Italy); 4, Capsian (and Iberian) facies; 5, Late Aterian; 6, Oranian; 7, Pre-Sabylian and Sabylian (Egypt); 8, Kenya Aurignacian; 9, other facies. S. A. Huzayyin, *842*, pl. III.

remains occur (see p. 859), through England and Belgium to the Crimea and the plains of south Russia (where it forms the earliest palaeolithic horizon) and into Palestine (e.g. Galilee, Judaean Hills and Mount Carmel) —this was probably Levalloisian and not true cave Mousterian. It may also have extended into Asia Minor and the Caucasus, to east Siberia and north China and into North Africa between Tunisia and Morocco and across the Sahara to 18° N. Here, as the Atérian[257] (from Bir el-Ater in Algeria), it is widespread on open sites and contains an evolved Acheulian form of hand-axe, with new features, especially small points with barbs, (probably used as arrow-heads), and unifacial and tanged pointed flakes. It probably survived much later (postpluvial) than in Europe.[258]

The source of the Mousterian was doubtless Asian. Rhodesian man[259]

(*H. rhodesiensis*) was possibly an independent development of the Neanderthal stock[260] and related to the Australian aborigines through the Talgai skull.[261]

Aurignacian. The upper Palaeolithic, comprising the Aurignacian, Solutrean and Magdalenian, was a time of rapid invention. The lowest division, first reported from Aurignac, Haute-Garonne, is the most important of the three and extends over Europe, Asia and Africa. Its greatest invention, evolved from the end-scraper, was the engraving tool or *burin* which has a narrow transverse edge like that of a chisel or gouge and first appeared in west Europe. Characteristic too were the carinated scraper, *La Gravette* flake, which evolved (apparently from the Châtelperron type) towards the end of the epoch, and a new and distinctive type, the Châtelperron point or backed blade (found in France, Poland and Palestine); this was smaller and neater than the rather triangular Audi blade, was curved, and had a cross flaking along the back for the user's fingers to press upon. These and other implements of this age were distinguished by their fine flaking or "Aurignacian retouch".

The succession of flake industries gives the five-fold division of the Aurignacian into the Audi (named after the rock-shelter of Abri Audi[262]), Châtelperron[263] of the middle Aurignacian (with split-base bone lance point—*point d'Aurignac*—keeled and nosed scraper and beaked graver), Gravette, Font-Robert and Grimaldi stages, these possessing double shouldered points. The "points" served as the tips of lances, darts, arrows or other hunting missiles.

Following the suggestion of D. Peyrony, the lower two divisions are often grouped together as the Périgordian, the middle Aurignacian being termed the Aurignacian, and the upper divisions being called the Gravettian. The succession may, however, be more complicated than this.

A great advance is signalised by the general introduction of bone, e.g. awls, from horse or reindeer. The use of mammoth ivory, which is rare in the lower but increases into the upper Aurignacian, is particularly characteristic of Moravia, e.g. Předmost.[264] Aurignacian art followed an evolutionary cycle not unlike that of the later Magdalenian (see p. 856). A prototype of the harpoon which became so characteristic of the Magdalenian (see below) has been found in France[265] (Charente).

In west Europe, the Châtelperronian (the earliest identifiable phyllum of the blade culture) and Gravettian follow each other and to some extent intermingle, giving the classic French sequence. This resulted from successive immigrations, superimposed perhaps on a certain amount of local variation and development. The idea that the Châtelperronian was an intrusive culture evolved from the lower Capsian of North Africa has fallen before the demonstration that the supposed prototype of their culture (Capsian) is much later in date (see below). It may therefore be regarded as of eastern origin,[266] generated in some as yet unidentified Asian centre[267] or directly evolved from the contact of Acheulian with Levalloisian,[268] possibly in central Europe or south Russia. Blade-cultures in Palestine and east Africa, in company with late-Acheulian, suggest an Asian origin for the blade-cultures.

The Aurignacian proper (middle Aurignacian), with its characteristic technique, statuettes and bone tools, features unknown in Africa, was intrusive and sprang from an Asian source,[269] possibly in the Iranian plateau. It can be traced across Europe through Lower Austria, Hungary, Rumania

and the Crimea into Transcaucasia, Anatolia and Palestine where it is abundant and covers a longer period than in the west. It is absent from Switzerland, Italy and Spain (except in the extreme north) and from Portugal where industries of Mousterian tradition persisted throughout the last glaciation.[270]

The Gravette industry was very widely distributed[271] in central and eastern Europe: it spread over the Russian plain from the Don westwards to the Carpathians and through the Moravian Gate to the upper Danube, all over west Europe to England and Wales, Belgium and France, and southwards into the Iberian Peninsula and Sicily. In Asia it occurred in Kurdistan and west Caucasia. The very distinctive female statuettes, made from mammoth ivory or fine-grained rock, are found in Austria, very abundantly in Russia and very sporadically in west Europe.

The Aurignacian is found in west and central Europe (fig. 163), including such celebrated open-air stations as Willendorf and Předmost, the "diluvial Pompeii". It continues into Poland,[272] south France (= Grimaldian[273]) and north Spain[274] (see above) and westwards into England[275] (Kent's Cavern, Paviland, King Arthur's Cave, Cae Gwyn, Fynnon Beuno and Creswell and surface finds in the open country, e.g. the Oolite ridge of Lincolnshire). Here the upper Aurignacian is a distinct local facies with semi-geometrical points and a special development of the proto-Solutrean points which replaced the typical laurel-leaf points in England, except in East Anglia. The Aurignacian wandered westwards through south Russia and south Poland and to the north of the Carpathians and also along the Danube. Unlike the development in the lower and middle Palaeolithic when Russia was very poor in these cultures—there were no true Chellean or Acheulian and less than 12 sites in all—almost every variety of flint industry known to west Europe is found in Russia during the upper Palaeolithic except the very specialised type of the "classical" Solutrean[276] (see below).

The Aurignacian has also been traced in Asia, as in Transcaucasia, Syria and Palestine,[277] India, China and Mongolia,[278] and the Yenisei in Siberia,[279] and progressed southwards through Africa.[280]

In many areas it was not disturbed by the Solutrean and Magdalenian but continued to develop independently. This "developed Aurignacian" has been assigned various names, including the Creswellian[281] (from Creswell Crags), which persisted into the Mesolithic and includes the open-air sites of the sand-dunes at Scunthorpe, Lincolnshire,[282] the Grimaldian[283] of Italy and the Côte d'Azur (see above) and the Swiderian of Poland (= early Mesolithic) and east Europe.[284] A revival in the British Isles of earlier forms by descendants of Aurignacians who found new uses for them has been postulated.[285]

The Sébilian,[286] a peculiar industry of diminutive Levallois cores and small truncated flakes in the Nile valley and Upper Egypt, first described from the Kom Ombo plain near Thebes, may be allied to the Aurignacian though of later date. With the Atérian (see p. 848), an industry in which Mousterian influence was strong, it may replace the blade cultures in this part of Africa which was apparently cut off from the main lines of development during these times. Thus in the Magdalenian, migration on a large scale came to an end and numerous local variations sprang up all over the palaeolithic world.

The Périgordian (see p. 849), to which the paintings of Lascaux in the Dordogne valley belong,[287] may have been derived from the same Asian root which gave the Capsian.

Africa during the upper Palaeolithic was something of a backwater: industries of Mousterian type lingered on until after the arrival of blade cultures in a relatively late stage of development. Such was the Kenya Stillbay stage of east Africa, which was a Levallois derivative in which some Acheulian elements survived. The palaeolithic industries of South Africa have been correlated as follows[288]:

	South Africa	*Europe and North Africa*
Later Stone Age	Wilton Smithfield C ,, B ,, A	Upper Capsian Capsio-Aurignacian
Middle Stone Age	Variety of industries with Mousterian affinities	Mousterian
Early Stone Age	Fauresmith Victoria West Stellenbosch	Acheulo-Mousterian Proto-Levallois Abbevillean

The Stellenbosch is regarded as a relatively pure offshoot of the same source as the lower Palaeolithic of North Africa; the Victoria West was evolved locally in dolerite country, more especially the Karroo; and the Fauresmith, descended from an amalgam of Acheulian and Levalloisian, may be equated with the Micoquean.[289] Smithfield A and B were definitely associated with rock-engravings in dolerite areas, and the Wilton with cave-paintings of the Union—the Wilton race, which was still in existence in the 16th century A.D.,[290] came from the north. The remains of Boskop and Florisbad types may belong to the middle Palaeolithic.[291]

The dominant industry in North Africa was the Capsian,[292] first discovered at Capsa in Tunis but of unknown ancestry. It is the Gétulian[293] of east Algeria and south Tunis and the time equivalent of the Atérian of the Morocco seaboard (see p. 848) which expanded from the Atlas Mountains over much of the Sahara to Egypt and the Sudan in the east (a protected survivor of the Mousterian[294]), and of the coastal Oranian[295] (also known as Ibero-Maurusian or Mouillian), a poor industry of tiny blunted blades, found in west Algeria between Tunis on the east and Casablanca on the west and well exemplified in the caves near Oran. The Natufian[296] of Palestine is roughly parallel with its latest phase.

Capsian implements were largely blades (of Châtelperron and Gravette types), blade scrapers and angle burins with (especially in later stages) geometrical microliths (trapezoid, rhomboid or triangular in shape) and large bone needles. The microliths are traceable into South Africa (the bushmen up to a recent date maintained a microlithic industry) and into Egypt, the Crimea and Phoenicia.[297] Ostrich egg-shells were used as vessels. Its art, superior to that of south Europe, depicted complete scenes instead of the isolated figures of the French cave paintings and drawings.

The centre of origin of the Capsian is obscure but may have been east Africa; the industry which was an inland development—the coastal industry was the Oranian—and belongs to the end of the Palaeolithic, may have entered Africa Minor already fully developed by way of the Sahara. At a later date it was destined to appear in Europe as the Tardenoisian (see p. 874).

Solutrean. The Solutrean (type station, Solutré,[298] Saône-et-Loire), though of very short duration, is the culmination of the art of flint making. Its flakes are flat and remarkably thin, sharp edged and perfectly symmetrical. They are distinguished by the beauty of their secondary or ripple flaking, achieved by a new technique of pressure by a bone or wood point instead of blows (W. J. Sollas[299] has described modern methods of pressure flaking). This was foreshadowed in the upper Aurignacian by the expansion of the retouches at the top and base of pedunculate points at Font-Robert and other places.

The Solutrean had three phases, each distinctive in its features and distribution: (*a*) the proto-Solutrean of the mountain caves of north Hungary, where it is primitive and pure and probably autonomous and had a background of Acheulian, and in Moravia where there are signs of admixture with Aurignacian characters, as well as in Belgium, north France and England[300] (e.g. Kent's Cavern, Paviland, Cae Gwyn, Fynnon Beuno, Uphill, Wookey Hole, Brixham, Creswell, Ipswich and other places in East Anglia); (*b*) typical or early Solutrean, with laurel-leaf points (*feuilles-de-laurier*), in Hungary, Moravia, Poland, Bavaria, west France and north Spain; and (*c*) late Solutrean with a revival of the upper Aurignacian shoulder-point (*pointe à cran*) confined to west France south of the Loire, and followed either by the extinction of the culture or its submergence in the rise of the Magdalenian. Thus the Solutrean, like the succeeding Magdalenian, is far more restricted than the earlier cultures[301] (fig. 163) being confined to the plains of Europe. It is generally thought to have originated in eastern Europe[302]—a "primitive Solutrean," with crude precursors of the laurel-leaf point lies between Mousterian below and typical Solutrean above in the caves of Pallfy, Balla and Szeleta in Hungary[303]—and to have spread westwards along the Danube into Austria, Moravia, Bavaria (e.g. Ofnet, Klause), Württemberg (Cannstadt), England (see above) and south France (where it is an episode interrupting the typological series Aurignacian-Magdalenian) and round either end of the Pyrenees[304] into north Spain—it has however been suggested that the culture originated here or in Africa from the fusion of Gavettian and Aterian[305] and that the proto-Solutrean of Hungary is not original but peripheral. Though present in Moldavia and Bessarabia,[306] the Solutrean is missing from the Crimea and Caucasus, from the country east of the Rhône, and from the whole of the Mediterranean region including Italy[307] where the Aurignacian continued throughout the entire upper Palaeolithic,[308] as well as from Sicily and North Africa. Contact between Mousterian man and the upper palaeolithic races led, however, to the evolution of a laurel-leaf point through Africa, including north, south and east[309]: some archaeologists believe the Solutrean originated in Africa as an offshoot of the Mousterians.

Magdalenian. The Magdalenian, named from the type shelter La Madeleine,[310] Dordogne, originated apparently in a renaissance of the earlier Aurignacian. Its flint implements, often badly selected and poor in quality, were less elaborate and less complex in style than the Aurignacian and Solutrean and display the minimum amount of finish and dressing. Most were simple flakes with generally poor or no secondary chipping; the technique had degenerated and the Solutrean touch was lost. The tools included a wide variety of smaller implements for fashioning bone and horn.

Magdalenian man worked in reindeer and deer horn, in lignite, and especially in amber.[311] Tools of bone, horn and mammoth ivory were

plentiful and developed with the utmost skill and art. The bone needle, which was sparing in the upper Aurignacian and Solutrean, now became abundant. Arrow and spear heads were adorned with simple incised designs. Multi-barbed harpoons, the earliest known, were the characteristic weapon and were used for fishing (fish are figured and at Mas d'Azil a fish is drawn pierced by a harpoon), projected possibly by propulseurs. They were single-rowed in the middle Magdalenian and double-rowed and richly decorated in late Magdalenian.

The Magdalenian, therefore, is subdivided into six phases[312] based upon the shape of the lance points in the lower Magdalenian (= 3 divisions) and of harpoons in middle and upper Magdalenian. The first three carry on the West Gravettian tradition of flint-work, with bone lance-points either forked or bevel-ended for hafting. In the subsequent stage there appears the new device of the barbed throwing-harpoon, with a haft at first merely notched, then barbed on one side (stage 5), and finally barbed on both sides (stage 6), first curved, then angular. The evolution was probably connected with the growth of forests in Europe (see ch. XLVIII), the increased difficulty of the chase, and the use of harpoons for hunting or fishing and of microliths which were probably attached to shafts for this purpose. The Magdalenian food gatherers occupied during the summer river mouths, lake-margins, bogs and other wet places, so that in addition to hard flint and stone, various perishable materials have been preserved—antler and bone axe and adze, sockets and blades, harpoons, arrow heads, net-making needles, bodkins and fish-hooks, wooden clubs, paddle-rudders, string nets and bark net-floats.

The Magdalenian was a French development. It arose from the Gravettian in the Pyrenees[313] and spread into north Spain,[314] central France, Switzerland,[315] Germany (more than 30 stations), Austria and Czechoslovakia[316] (batons, needles and double-barbed harpoons have been found as far east as Moravia) and less frequently into Belgium and atypically into England[317] (Wretham Heath, Kent's Hole, Creswell, Cheddar, Colne valley, Aveline's Hole, Gough's Cave, Victoria Cave). It is unknown in eastern Europe, in south Spain, Italy (see above) and throughout Africa.[318] Like the Solutrean, it is absent from India where there appears instead a mesolithic culture with typological relationships to the Capsian of Syria and Africa.[319] Upper palaeolithic decorated caves occur in central and south-west France, the Pyrenees and central Spain—outside this region they are known only at Petershöhle in south Germany and at Romanelli in Italy and in Sicily.

During the Magdalenian, migration on a wide scale gave way to local variations of the culture already in possession. Thus we have in Italy the Grimaldi, in south Russia a degenerate industry of Gravettian tradition, in Palestine and possibly the Crimea a hybrid Aurignacian, in Nubia and Upper Egypt the Sébilian, and in north Germany the Hamburgian (see p. 880) of the Older Dryas period, though the Magdalenian survived in north Germany into later times,[320] e.g. at Rissen near Hamburg. In England, the upper Palaeolithic remained basically the Gravettian, and the Creswellian shows the typical blade-knife ever diminishing in size.

Life of palaeolithic man. Palaeolithic man had an upright gait and posture—his hands were free to capture and kill his prey, to skin and cut up his animals, to erect protections against the weather and to perform numerous other tasks. To judge from his known remains (which sometimes show pathological conditions[321]), he lived but a short life,[322] like mesolithic man,

and seemingly rarely died from natural causes. Dependent upon the chase for his food and upon pelts of horse, bison and reindeer for clothing, he hunted reindeer, especially in upper palaeolithic time (late Magdalenian of south-west Europe and the Hamburgians and Ahrensburgians of north Germany and northern Holland) when hunting was by barbed harpoons—at Munzingen reindeer remains formed 5% of the total booty, at Kesslerloch 79·4% and at Schweizersbild 75%[323] and at Stellmoor almost 100%[324]—horse, e.g. at Solutré, mammoth, e.g. at Předmost, bear, e.g. at Mixnitz and in the high Alpine caves[325] (especially in late autumn), *Bison priscus*,[326] cattle[327] and deer—70% of the animal remains found at Chou-K'ou-tien were deer. Smaller animals, e.g. hare, fox and marmot, were of little importance, and in the case of lion, panther and hyaena man was probably the hunted and not the hunter. Like modern Eskimo he sewed the skins together into clothes, using bone needles and tendons of reindeer for thread: stylish scratched figures occur in the Moravian Palaeolithic.[328] Skins were probably used for holding water and for the making of shelters and windbreaks. Primitive spears were replaced by javelins, soon hurled by a throwing stick, and these in turn by bows and arrows. Birch-pitch was probably used in upper palaeolithic and later times to fix flint blades into their handles and to secure arrow heads to their shafts.[329] He inhabited sea-shores and gathered limpets and mussels in Neanderthal and Grimaldi times[330]—while his glacial shore-sites are generally now submerged (see p. 1355) those of interglacial times are still accessible, e.g. the Abbevillian and Acheulian of the Milazzian and Tyrrhenian of Portugal and Morocco and the Levalloisian in Jersey. Apparently he did not practise fishing except in upper palaeolithic times, i.e. from the Aurignacian on, since while fish remains are almost unknown from earlier layers[331] they are abundant in the upper Palaeolithic; fishing gear, e.g. the fish-spear is known, and fish are represented in cave-art[332] (e.g. pike, trout, salmon, flat fish, tunny). Fishing may have been done by striking fish through holes in the ice, by the use of line and gorge-hook, net and the funnel-shaped trap. The boat came in with the Mesolithic,[333] e.g. Maglemose. Palaeolithic man may have killed birds with a sling,[334] though many of the bird remains are probably attributable to birds of prey or to small rodents or fox or arctic fox.[335] The Hamburgians at least seem to have shot birds by bow and arrow while in flight.[336] For his personal decoration[337] he used shells, fossils, minerals and mineral substances (amber, jet, cannel, quartz, fluor spar and ochre), bones and pierced teeth, made into bracelets or necklaces or sewn into fur garments and hoods. That he subsisted partly on vegetable food is suggested by the hackberry endocarps (*Celtis barbouri*) associated with Peking Man.[338] Rock-paintings of eastern Spain show that honey of wild bees was collected in upper palaeolithic times.[339] Finds in China and at Ofnet, Krapina, Ehringsdorf and Grotta Guattari seem to prove that, contrary to an earlier view,[340] *Sinanthropus*, Neanderthal and other palaeolithic men were cannibals.[341] Human bones fashioned in Italy into all kinds of implements[342] seem to point to the same conclusion. Apart from his defence by fire he was vulnerable to attack by the wild animals. This he overcame by carefully sited positions,[343] e.g. in caves or at their entrances—here belong more than half of all palaeolithic stations—on the banks of rivers and especially within their meanders, e.g. Markkleeberg, Hundisburg, Amiens and Abbeville, or on the promontories of lakes, e.g. Rabutz, Taubach, Ehringsdorf and Weimar.

He was ignorant of agricultural operations (though wheat of Magdalenian age has been claimed[344]) and, save for the dog at a late period, had no domestic animals, though E. Piette[345] and T. Studer[346] suggested he had tamed the reindeer. He was unaware of the arts of spinning, weaving and, with an occasional and doubtful exception, of the making of pottery[347]—the exceptions are in the Mousterian of Spy,[348] the Mousterian or lower Aurignacian of Ipswich,[349] the upper Palaeolithic of Belgium[350] (cf. p. 874) and the upper Aurignacian ceramics representing animal heads and anthropomorphic statuettes (but not vessels) in Moravia[351]—the earliest ceramics are otherwise from the early Campignian of Belgium and the early Tardenoisian of Brandenburg. Cro-Magnon man at least may have been able to count.[352]

During the warmer periods palaeolithic man inhabited open plains and broad wooded valleys, living in light artificial dwellings or tents of the kind depicted in the tectiforms of Franco-Cantabrian cave art[353] (see below)—the tectiforms may however represent traps used in hunting animals—or used in Magdalenian times,[354] or in winter houses sunk into the ground as in south Russia.[355] Here the mantle of loess has sealed down the open stations of the upper palaeolithic hunting tribes, preserving even the plans of their houses (the oldest artificial dwellings known in the world) which belong to the same general family as those in use more recently in Greenland and the extreme north of America. Similar rectangular hut sites of palaeolithic age have been found in Czechoslovakia[356] while round dug sites of Aurignacian age are known from the Danube basin.[357] A wind break of wood may have been used in the Thames valley.[358]

The mode of life in the forested Mediterranean is not known.

During the colder periods, early man lived in or at the mouth of caves or shelters with wind-break screens of boughs and skins and an artificial pavement underfoot,[359] e.g. at Kesslerloch: dampness of the caves caused diseased swellings and inflammation of the bones of both man and animals. He knew the art of fire,[360] as hearths, ashes, charred wood and bones and pot-boilers (even on lower palaeolithic sites) show, e.g. at Téting near Metz, in the Chellean of Torralba, in the "Alpine Palaeolithic" and at Chou-K'ou-tien ("*Cereis blacki*"), as well as in the pre-palaeolithic deposits of the South African man-apes, though since signs of fire are absent from some sites it is possible that some lower palaeolithic groups ate their meat raw or perhaps dried like *biltong*.[361] By the use of fire he had security at night from predatory creatures, and he was able to move into colder climates, cook food, shape tools and hunt animals (see p. 1398). He may have used primitive lamps fed with bear fat[362] as a protection against cold, in the preparation of food and for lighting. Where suitable wood existed this was also used for this purpose.[363] An elaborate ritual of interment[364] was practised, as at La Chapelle aux Saints and Le Moustier: the crania were separated from the bodies and placed facing the setting sun, as at Ofnet,[365] while at Cro-Magnon the bodies, fully extended, were buried with offerings of food. Ceremonial burial was apparently relatively common during the upper Palaeolithic and there are suggestions of magical practices.[366] These were performed in recesses in the caves which are difficult of access. The cave bear was connected with his religious conceptions.[367]

The palaeolithic population was probably very sparse. Thus the population of Britain[368] during upper palaeolithic times may have been only 250 during the winter months, during the Mesolithic 3000–4000, during the

Neolithic 20,000 and during the Middle Bronze Age 30,000–40,000 The number of Neanderthalers living in Europe at any one time may have been a few hundred or a few thousand. At the end of palaeolithic times the world's population was probably not over 10 million.[369]

Palaeolithic art. While there are indications of primitive artistic activities of Neanderthal man,[370] art was practised only by upper palaeolithic man. Art is unknown from Châtelperron time but from the very base of the Aurignacian ivory feminine statuettes appear which later are replaced in various Bavarian sites by animal figures. The inception, development and decay took place in two independent cycles of evolution, the first of Aurignacian and Périgordian age, the second of Magdalenian age,[371] examples of Solutrean art being relatively few, as in Charente,[372] and possibly executed by Aurignacian man in Solutrean times.[373] The Lascaux paintings of the Périgordian which link the two great centres of rock-painting of Spanish Levant and Aquitaine-Cantabria, confirm the upper palaeolithic age of the rock-art of eastern Spain.

Magdalenian engravings of stone and bone occur in Belgium[374] and a number of upper Pleistocene drawings, etc., are known from Switzerland.[375] English examples[376] are rare; they include a carved bone (horse) near Sherborne, Dorset; an incised figure of horse and engraved masked horse from Creswell; three pieces of engraved bone representing possibly bison, reindeer and rhinoceros from the same locality (formed by the action of roots?[377]); engravings of cervidae from Grimes Graves; and ten red bands on the walls of Bacon's Hole, Gower, south Wales.

This upper palaeolithic art, first discovered in the cavern of Altamira by M. de Santuola and described by E. Lartet and H. Christy,[378] may have been the creation of an artist caste and of ceremonial and religious or magic origin,[379] especially the custom of hunting magic as practised by living primitive peoples. It included sculpture in the round—the middle Aurignacian ivory sculptures represent mammoth, panther, bear, wild horse and reindeer[380]—and in relief, drawings, paintings and engravings being made possibly from direct studies of dead animals.[381] Chronological stages of development have been recognised.[382] Piette,[383] by the relation to the floor deposits and the superposition of mural figures, subdivided his *Glyptique* into *equidien* (*elephantien* and *hippiquien*) and *cervidien* (*rangiferien* and *élephien*). These stages show a progressive degeneration of naturalist engravings towards conventional and simple geometric patterns—the art was also much more schematic in Poland and Moravia—which included the "tectiforms" which are often interpreted as rudiments of writing or at least a graphic expression of precise ideas (see above).

The materials used were crayons, powdered ochre, iron ores, carbonaceous matter, pyrolusite and kaolin, with mortars, scratchers and engravers. The ochre, etc., was either applied as a paste by finger, by brushes made of a chewed branch, or by pads of fur or feathers, or was blown on to the surface as a powder through a "blowpipe" made of reed or hollow bone.[384] The leading motif is the animal form; fish, deer, bison, horse, cave bear, reindeer, red deer, mammoth, woolly rhinoceros and occasionally musk ox, great Irish deer, lion, hyaena and glutton were portrayed with striking realism—the drawings have proved very useful for the reconstruction of the mammoth,[385] woolly rhinoceros[386] and cave bear.[387] Game was predominant, including the horse (in France), red deer (in Spain) and bison. Fish, batrachians and

reptiles in palaeolithic art have been described and figured[388] and the animals have been listed.[389] Birds are relatively rare, plants still rarer, and reptiles and invertebrates practically unknown.

Pictorial art[390] on the walls of caves and rock-shelters is restricted to the district surrounding Les Eyzies in the Dordogne, the northern slopes of the Pyrenees, the Cantabrian Mountains and the Mediterranean coast of Spain. Decorative art on objects of utility, the so-called *art mobilier*, is much more widespread, extending to Russia in the east and England in the west.

Human palaeontology. Since A. Boué discovered, in 1823, a palaeolithic skeleton in the Belgian loess, remains of over 100 individuals of palaeolithic man have been found, most of them in Europe. Excellent summaries[391] of the anatomical details have been published while the *Fossilium catalogus: Hominidae fossilis* gives the complete world literature up to the year of publication (1936) and the *Catalogue des Hommes fossiles* (*CR. C. G.* Algiers, 5, 1953) the literature up to 1952.

The palaeolithic skulls may be tentatively referred to the following horizons[392]

Magdalenian: La Madeleine, Laugerie-Basse, Cap Blanc, Les Hôteaux, Mas d'Azil, Grottes des Hommes, Castillo, Obercassel, Balla, Duruthy, Chancelade, Placard, Sordes.
Solutrean: Brünn, Klause, Laugerie-Haute, Le Roc, Neu-Essing, Brux, Předmost.
Aurignacian: Engis, Camargo, Castillo, Combe-Capelle, Cro-Magnon, Enzien, Grottes de Grimaldi, Paviland, Solutré.
Mousterian: Steinheim, Ehringsdorf, Mount Carmel, Pech de l'Azé, Crimea, Neanderthal, Galilee, Gibraltar, Jersey, Rome, La Naulette, Krapina, La Quina, La Chapelle aux Saints, La Ferrassie, Le Moustier, Malta, Petit Puymoyen, Sipka, Spy (see below).
Acheulian: Ehringsdorf, Krapina, Taubach, Swanscombe.
Abbevillean: Mauer?

The oldest skulls are those of Mauer, Heidelberg, Trinil and Peking.

The earliest Pleistocene man stood erect: even the Dryopithecinae had an upright or semi-upright posture. Broadly, three stages of increasing morphological complexity may be recognised: the early stage, of *Sinanthropus* and *Pithecanthropus*, placed generally in the first interglacial; the Neanderthal stage (including Heidelberg man and *Africanthropus*) of Mindel-Riss and Riss-Würm interglacial; and a third stage of *Homo sapiens fossilis* (*Homo sapiens diluvialis*) of the last glaciation—S. Sergi has termed them respectively "Protoanthropus", "Palaeanthropus" and "Phaneranthropus". Nevertheless, remains with characters of *Homo sapiens*, it is claimed, occurred in Europe before Neanderthal man, viz. Denise (1844), Castenedolo (1860/69), Olmo (1863), Galley Hill (1888), Piltdown (1912), Ipswich (1914), London (1925), Swanscombe[393] (1935) and Fontchévade (1949). Of these, the last two only should now be retained; the fluorine method proves that the Galley Hill remains, like those of Dartford and Bury St. Edmunds (see p. 859) are end-Pleistocene or early Holocene.[394] The rarity of pre-Neanderthal skeletal remains may be due to the fact that these early men lived in open country, rarely frequented caves and perhaps neither buried their dead nor practised head-hunting.[395]

Java man. Java man, *Pithecanthropus erectus*, is based upon discoveries[396] made in 1891, 1937 and in later years in the Trinil Beds of central Java. The remains include a female cranial vault, small and dolichocephalic, with ape-like supraorbital crests and low receding frontal bone, three molar teeth and a thigh bone essentially similar to that of modern man. Unfortunately, not only is the actual relation to man obscure—some anthropologists,[397] for example, refer the remains to a gigantic gibbon—but the remains are of uncertain age since they are unrelated to the Pliocene or Pleistocene of the northern hemisphere, had no associated flint industry—while the chopping tool industries of southern and eastern Asia may represent the cultures of men of the *Pithecanthropus-Sinanthropus* stage of evolution,[398] the Sungiran implements belong probably to *Homo soloensis*[399]—and had neither elephant nor horse but a purely Asian fauna. E. Dubois,[400] the original discoverer, placed them in the upper Pliocene, as did others[401] on the evidence of the plants and animals (= species of hippopotamus and Stegodon). Others put them in the Cromerian[402] or in lower or middle Pleistocene[403] (the fauna resembles that of the Narbada valley of India) or in the upper Pleistocene.[404]

H. modjokertensis[405] is a juvenile specimen of *Pithecanthropus erectus* or more probably of *P. robustus*.[406] *Homo soloensis*,[407] based on eleven skulls and on skull fragments, found in the Solo River terrace near Ngandong, central Java, is a distinct form descended apparently from *Pithecanthropus*. It may be a link with the modern Australoids[408] or with Neanderthal man.[409] *Pithecanthropus* was probably short in stature (1·5 m) with beetling brows, sloping forehead, powerful jaws, rather large teeth, strongly developed muscles and low intelligence.

The Djetis forms include *Meganthropus paleojavanicus*, *Pithecanthropus dubius*, *P. modjokertensis*, while the Trinil beds have *P. erectus* and the Ngandong beds *Homo soloensis*. Sumatra has yielded remains of palaeolithic man,[410] viz. *H. kamparensis*. The Mauer lower jaw which has usually been regarded as a precursor of Neanderthal man has recently been correlated with *Pithecanthropus*.[411]

Peking man. Peking man,[412] *Sinanthropus pekinensis* Black[413] (*Pithecanthropus pekinensis*[414]), based upon about 45 individuals, males and females, adults and children, of which no single specimen is complete and many consist only of teeth, is an independent hominoid type, distinctly inferior to Neanderthal man and showing definite anthropoid peculiarities in many particulars.[415] The remains were found in the search for the source of "dragon stones" (mammoth, etc.) at Chou-K'ou-tien, *c*. 60 km south-west of Peking, with much charcoal and evidence of the use of fire,[416] a bone and antler industry[417] and a few thousand artefacts[418] of greenstone and vein quartz, which being atypical it would be vain to assign to any western type.

Although the jaw presents the same simian peculiarities which aroused doubts when the Piltdown jaw was found (see below), *Sinanthropus* belongs to a generalised and quite progressive type not far removed from the hominoid which gave rise to Neanderthal, Rhodesian and other forms.[419] While possibly more primitive than *Pithecanthropus*[420] or a Chinese variant of this[421] and identical with *Homo* (*Javanthropus*) *soloensis* of Java,[422] it links features of *Pithecanthropus* and *Eoanthropus*.[423] Earlier hominoids of the Sino-Malayan area were the following more primitive and gigantic types[424]: *Gigantopithecus blacki*, *Meganthropus paleojavanicus* and *Pithecanthropus robustus* (= *P. modjokertensis*). *Africanthropus njarasensis* of Kenya has

been thought to represent the *Pithecanthropus* stage in Africa[425] and to have evolved on parallel lines. It is, however, now generally regarded as a specialised type and as upper Pleistocene in age in spite of its archaic appearance. *Meganthropus africanus* is the African giant form. To *Pithecanthropus* may also belong the jaws and other skull fragments recently found at Ternifine in Algeria and named *Atlanthropus mauritanicus* (Arambourg, 1954, 1955).

"Piltdown man". *Eoanthropus dawsoni*, the "dawn man", was founded upon fragments of two female skulls, a mandible and a molar (of which excellent radiographs have been published[426]), which were discovered at Piltdown[427] in a shingle of the Sussex Ouse. The cranium is modern in its capacity and its general configurations and dimensions whereas the mandible was distinctly anthropoid in its projecting canines and absence of *spina mentalis* so that some writers[428] considered the jaw to be that of a chimpanzee and separate from the cranium. That two complementary parts of a head belonging to two distinct types should occur together was, however, regarded as more than a coincidence.[429] Recently both skull and jaw have been proved to be spurious and to have been "planted" by some person unknown.[430] The detection of this forgery came unfortunately too late to do more than give a reference here to the discovery of the detection.

The age of the remains has long remained uncertain[431]: they have been regarded as upper Pliocene or Chellean or coeval with the High Terrace of the Thames. The fluorine method (see p. 1525) proves that the cranium is not older than early upper Pleistocene[432] (Riss-Würm interglacial). It was associated with two animal groups,[433] one a remanié and rolled series of *Mastodon arvernensis*, *Dicerorhinus etruscus* and *Elephas* cf. *planifrons* ("Stegodon") of Villafranchian age, the other typically Pleistocene, including beaver, horse and deer with burnt flints,[434] flint implements of indefinite eolithic or Pre-Chellean character, and a bone implement made from the femur of *Elephas meridionalis*[435] (cf. p. 838). The cranium has been referred to *Homo sapiens* of an essentially modern type, and not older than Neanderthal man[436] and probably Neolithic.[437]

A possible successor of early palaeolithic skulls has been found at Swanscombe[438] in the 100-ft terrace of the Thames with implements of Acheulian I and III. Keith[439] believes the London Skull[440] (*H. londonensis*) and Bury St. Edmunds fragment have affinities with Piltdown man and, like the Swanscombe skulls, are later modifications. Morphologically, Swanscombe woman belongs to *H. sapiens*,[441] and may be of the Cro-Magnon type.[442] The Galley Hill remains found near Swanscombe in the 100-ft terrace of the Thames, though referred to this horizon,[443] are a later burial.[444] A lower palaeolithic skull has been recently found in France[445] (Charente) for the first time (see pp. 845, 864).

Neanderthal man. Neanderthal man[446] (*Homo neanderthalensis* King; *H. primigenius* of L. Wilser[447] and other German archaeologists) is based upon many skeletal remains which, though first found in 1856 in the Neanderthal valley of Germany, are most numerous in France and Belgium—Hrdlicka[448] has tabled the Neanderthal fossil remains in their order of discovery. Later finds have extended the range to Hungary,[449] Jersey,[450] north-east Spain[451] (Banolas), Malta,[452] Gibraltar,[453] Italy,[454] Galilee[455] (*Palaeanthropus palestinus*, *Homo neanderthalensis palestinus*), the Crimea,[456]

Tashkent,[457] Siberia,[458] near Bokhara,[459] North Africa (Tangier[460]) and Somaliland and Abyssinia.[461] Rhodesian man (see p. 871), of uncertain age, was the African type, and *H. soloensis* (see above) the east Asian representative.[462] Up to the present the remains of about 100 Neanderthal individuals have been discovered.

Neanderthal man was of moderate stature (rarely more than 5 ft 4 in.; 1·63 m) and of heavy and stocky build with a slouched appearance required by the absence of the fourth or cervical curvature. He had a good-sized, thick and long skull with pronounced supra-orbital torus, low forehead and vault, protruding occiput, large and full upper maxilla, large nose, teeth and jaw, receding chin and a low stage of brain development. He was less muscular and vigorous than the Acheulian race.[463]

The discovery at Spy in 1886 of a Neanderthal skeleton under undisturbed stalagmite and associated with artefacts resembling those Lartet and Christy described from the lower deposits of Le Moustier, proved that Neanderthal man was Mousterian man, the *H. mousteriensis* of French archaeologists. Later discoveries at Gibraltar and elsewhere confirm this relationship. The word Mousterian, therefore, should be reserved for the industries of Neanderthal man.

Neanderthal man, following the investigations of G. Schwalbe (1899), is generally regarded as a distinct or aberrant race, which evolved from man of lower palaeolithic time,[464] including *Pithecanthropus*. He died out at the end of the Mousterian[465] as the result of the exterminating action of *H. sapiens*[466] or, more probably, of a degeneration brought about by climatic deterioration (see p. 1029), an unhealthy cave life (smoky and damp) and inbreeding.[467] Thus an abrupt hiatus occurs in the cultural sequence; Neanderthal remains are morphologically distinct and specialised; transitions into later skeletal types are wanting[468]; the remains of Neanderthal man, dating from the earlier part of the Mousterian epoch, are often less "Neanderthaloid" in their characters and approximate more closely to *H. sapiens* than do the classical types of later date; and the evolution into *H. sapiens diluvialis* is biologically unlikely in the brief span the geological evidence suggests. Because of this break the Palaeolithic has been divided into a Protolithic below and a Miolithic above.[469]

It is usually thought that Neanderthal man was replaced by Aurignacian man who penetrated from the east. Verneau,[470] on osteological grounds, countered this opinion, averring that the Australian native is closely related to Le Moustier man and that certain features in neolithic and modern skulls are to be explained by atavism (see below). Hřdlicka,[471] with others, expressing views not very dissimilar, concluded that Mousterian man evolved into Aurignacian man because of hard winters which reacted on his food, clothing, shelter and the fauna, and intensified natural selection. He appealed to the transition implements, e.g. Abri Audi (see above), the morphological instability of the skeletal remains, their evolutionary nature, e.g. in dentition and head form, the absence of a pre-Aurignacian man in western Asia and North Africa, the improbable invasion of Europe by a new race as the Glacial period approached its maximum cold, and the occurrence in modern individuals of transitional features reminiscent of the Neanderthalers. Evidence, in the form of skulls and implements, suggests that the Neanderthal strain survived into Aurignacian time in central Europe[472] as it did in Palestine where the skeletal remains exhibit a remarkable mingling

of the characters of Neanderthal and modern man.[473] F. Weidenreich[474] also suggests that human remains from Russia and central Asia may be transitional and that Neanderthal man gave rise to modern man. It is indeed possible that while the specialised types of Neanderthal man in Europe died out the more generalised type led through Acheulian man to modern man.[475]

The wide variation in the jaws, skulls and limbs of the Neanderthal remains may be correlated with cultural differences observable in middle palaeolithic time. Keith,[476] for example, recognised various modifications of the general type—the Heidelbergian, Chapellian, Ehringsdorfian, Krapinian and Palestinian.

H. heidelbergensis Schoetensach, a jaw found in 1908 in the Mauer Sands of Heidelberg[477] (associated with bone artefacts?[478]) and placed in the Cromerian[479] or the Günz-Mindel interglacial,[480] may be a precursor of *H. neanderthalensis*[481]: *Pithecanthropus* has been regarded as its forerunner.[482]

Upper palaeolithic races. The upper palaeolithic skeletal remains, the skulls of which have all been measured and photographed,[483] are dolichocephalic and often subdivided into several races[484] which are regarded as early representatives of the white stock with certain negroid tendencies[485] and evolved possibly in south-west Asia.[486] The best known is the Cro-Magnon race which was probably preceded by the men of Grimaldi and Combe-Capelle and followed by those of Chancelade. They belong to *Homo sapiens fossilis*.

The Cro-Magnon race,[487] known from abundant remains first unearthed in 1866, was tall (5 ft 10 in. to 6 ft 4 in.: 1·78 m to 1·93 m) and straight and strongly jawed with a long head possessed of large cranial capacity, prominent chin and nose, broad face, and much reduced brow ridges. Skeletal remains are known from Cro-Magnon (fig. 164), Aurignac, Grottes de Grimaldi, Combe Capelle[488] (by some regarded as racially distinct (lower Aurignacian) but possibly not so[489]), Engis, Solutré, Předmost, Willendorf, Paviland, Camargo, south Italy and Morocco,[490] and from the Altai Mountains.[491] Mongoloid in character, he is regarded by some as the creator of the middle Aurignacian industry,[492] by others, much less probably, of the Magdalenian culture.[493] Its most likely ancestor is the Skhül type of Palestine.[494] The eastern dolichocephalic group is associated with the "eastern" Gravettian, the western brachicephalic group with the "western" Gravettian.

The Chancelade race[495] who probably descended from Cro-Magnon man[496] was of low stature and resembled the modern Eskimo in osteological characters, including the vertical sides and keeled roof of the brain case, the prominent cheek bones, wide zygomatic arches and shape of the lower jaw. The ethnic affinity of this existing peripheral race, though denied,[497] is often asserted.[498] Arguments in its favour are the great resemblance of the implements,[499] e.g. arrow heads, arrow straighteners, sculptured figures and line engravings, recent craniological comparisons,[500] the "Thulean" and other early Eskimo cultures of Alaska[501]—the Thulean culture was associated with winter houses of stone, bones or turf and with sea animals—and the earth-houses of the far north which may derive ultimately from the semi-subterranean houses known to have existed on the fringe of the glaciated area of the Old World in upper palaeolithic time.[502] Contrary to an earlier view which derives from Rink and referred the origin of the Eskimos to a comparatively restricted centre in the North American continent near Hudson Bay,[503] it is thought that Chancelade man supplanted Cro-Magnon man and retreated

northward with the reindeer at the end of glacial times—linguistic connexions with Tibet corroborate this wandering across Asia.[504] T. Mathiassen,[505] who with K. Birket-Smith linked the origin of the Eskimo with that of the American Indian, demonstrated that the Thulean culture had its roots in the west along the Alaskan or Siberian coast. Developmental stages in art, harpoon heads and numerous other implements have provided the framework of a relative character that carries Eskimo culture back for probably 2000 years. The Old Bering Sea, Ipiutak, Punuk, Birnirk, Dorset, Thule and Inugsuk are the various recognised stages, some of which are contemporaneous with one another. While the Old Bering Sea and Ipiutak exhibit unmis-

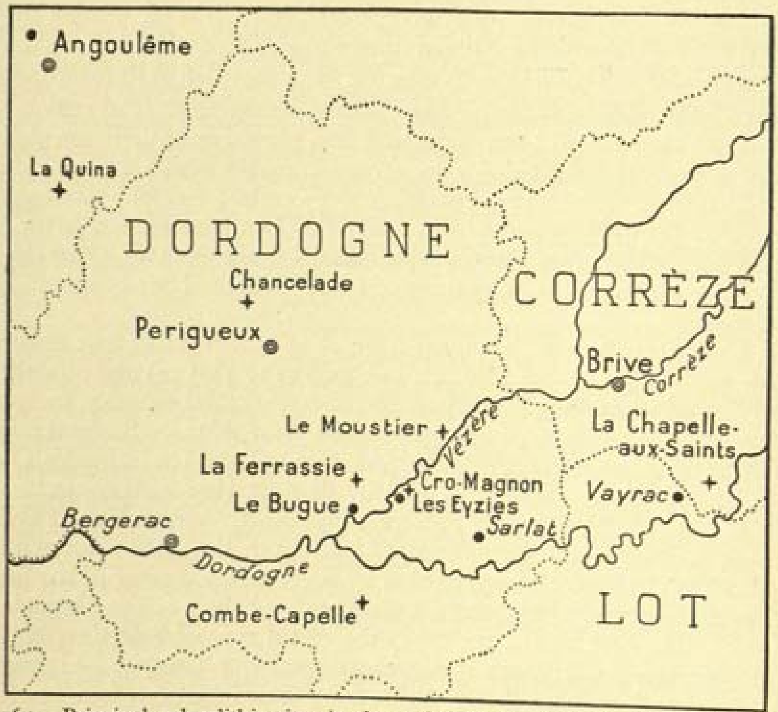

FIG. 164.—Principal palaeolithic sites in the region of the Dordogne which have yielded human remains. M. Boule, *174* (3), p. 213, fig. 132.

takable affinities with mesolithic and neolithic horizons of north Europe and south Siberia, a wide gap separates the Eskimo culture from the Baikal culture of Asia both in space and time. The cul-de-sac of Greenland was only invaded about 1000 years ago.[506] From the primal Eskimo-generic centre situated between Lake Baikal and north-east Asia,[507] the "jumping off place" for America, the basic prototype of the American Indian and the Eskimo travelled gradually and disconnectedly across Bering Strait into North America. Remains similar to those of the Eskimo are found on the Aleutian Islands,[508] where a history extending back perhaps 4000 years has been traced, and small end-scrapers and conical cores, identical with those collected in large numbers in the Gobi desert,[509] sustain the conclusion. Studies of the Eskimo crania also suggest arctic Asia as the original habitat.[510] Central Asia has been regarded as the original home of all the arctic peoples.[511]

Nevertheless archaeology has not yet discovered the origin of the Eskimo nor any habitation site in Alaska older (by radiocarbon dating) than *c.* 6000 years.[512]

While we are forced on theoretical grounds to assume that man originally entered North America at Bering Strait, archaeological work in this region has yet to reveal any trace of these earliest immigrants; the cultural links between the upper Palaeolithic and the present Eskimos of North America if they exist have also to be discovered. Modern Eskimo art is possibly remotely connected with palaeolithic art and the two oldest known phases of Eskimo art (Old Bering Sea Style I and Dorset) have affinities with palaeolithic and especially with mesolithic art.[513] The Eskimo dog is apparently a wolf hybrid of the *Canis inostranzewi*.[514]

The Brünn race,[515] founded on osteological remains from Brünn (Moravia), includes finds at Brux and Předmost and the Galley Hill skull (see p. 857).

Africa has yielded a number of anthropoid skeletal remains,[516] including the various remains of Capsian and Oranian man,[517] the Australopithecinae of South Africa,[518] viz. *Australopithecus africanus* or *Plesianthropus transvaalensis* (Taungs skull), and, very closely related, *Paranthropus robustus* which were pigmy ape-men of Pliocene age—they were associated with many extinct mammalian genera—which may well represent the ancestral stock from which man took his origin[519]; the remains of Kanam and Kanjera which are of uncertain age[520]; the Olduvai skeleton[521] which was probably a late burial[522] and not contemporaneous with the bed containing Chellean-Acheulian implements in which it was found. The Asselar skeleton (see p. 1115) had indubitable negroid affinities and markedly resembles the South African Basuto. The negroes, however, are seemingly of no great antiquity and have yielded no fossil remains.[523]

Recent theories of the origin of the species of *Homo sapiens* and its relation to other known species of man conflict as to the assumed evolutionary process. According to F. Weidenreich, *Pithecanthropus* and *Sinanthropus* progressed in parallel through a Neanderthal stage leading to *Homo sapiens*. Hybridism among different species is suggested by others, e.g. Patterson and Coon. McCown and Keith believe that *H. sapiens* was a middle or upper palaeolithic offshoot, simultaneous with Neanderthal man, from an intermediate form, e.g. Mount Carmel man.

In general, viewing all known fossil men, they seem to fall into three evolutionary stages, representing three genera which are partly successive and partly contemporaneous: they are the *Pithecanthropus*, *Homo neanderthalensis* and *H. sapiens* or modern stages.[524]

Home of man. Although Europe may have been the home of man,[525] it is more likely that, as in other zoological respects, it was a terminal region and not a centre of palaeolithic evolution.[526] The independence of its palaeolithic industries is not original but the result of successive waves which spread outwards from Asia.[527] Darkness, however, still envelops the cradle of palaeolithic man (cf. p. 836), for no fossil evidence at present exists to show how the man-like apes of Miocene time were transformed into the ape-like men of the Pleistocene. Since human limbs had already attained their final refinements of shape and proportions at the beginning of the Quaternary, the point of divergence of the evolutionary line leading to man from that leading to modern large anthropoids must have been fairly remote.[528] An African or Neanthropic origin,[529] first enunciated by Darwin in 1871 because gorilla

and chimpanzee, the surviving higher apes most nearly related to man, inhabit that continent, is not excluded for the upper Palaeolithic by the distribution of the Aurignacian, Capsian and Magdalenian cultures which lose their distinctiveness when traced from the European, African and south-west Asian region. The discoveries of the Australopithecinae lend support to this view though the Australopithecinae, while closely related to the ancestral stock which gave rise to the Hominidae,[530] should be excluded from human ancestry since their teeth are too large, their brain too small, their premaxilla is ape-like and their age is geologically too young.[531] Though the hand-axe cultures are now generally assumed to be African in origin, the migration routes of Heidelberg and Neanderthal man are still unknown, and Uganda was probably the centre of diffusion of the pre-Chellean pebble cultures and witnessed the steady evolution of human industry that was probably set in motion during the Pliocene. The Grimaldi skeletons[532] in Europe are alone African in character (cf. p. 871); for though they are dolichocephalic like the Cro-Magnon and Chancelade races, they have the broad nose and the strongly projecting mouth and teeth of the African negroids. Additional facts pointing to the African origin of man are the Miocene *Proconsul* of Tanganyika, the numerous Australopithecines of the fissure deposits of the Transvaal and the abundant palaeolithic industries of Kenya, Belgian Congo, Rhodesia and South Africa.

An Asian or Palaeoanthropic origin, often asserted,[533] is suggested by the widely distributed Mousterian and Aurignacian implements in that continent, by the continuous series of human skulls connecting the ancestral apes with modern man and arranged in successive rings round the presumed Asian centre, by the almost contemporaneous occurrence of primitive types of Hominidae on the eastern edge of Eurasia (Java, Peking), and by the backwardness of Europe as compared with Asia at corresponding epochs of the Palaeolithic.[534] Such an origin is now held for the flake-cultures (see p. 841), though the recent discovery of Neanthropic remains at the Cave of Fontéchevade (Charente) in a horizon which yielded flake-tools (Tayacian) presents a serious difficulty.[535] Suggestive also are its central position, its importance in the evolution of the domestic animals and its climatic change in Miocene and early Pliocene time.

The earth during the Pleistocene passed through many physical and climatic changes of the utmost importance. The sea-shores wandered widely (see p. 1355)—the Persian Gulf, for example, was alternately wet and dry, and the coasts of west Europe were displaced through 500 km; the ice-sheets covered 30% of the land-surface; and glacial and interglacial, pluvial and interpluvial oscillations (through 1000–2000 km) affected wide regions. Taylor[536] has suggested that the environment best suited to man, i.e. the woodlands bordering the steppes, swung north and south with the fluctuations of temperature. The climatic stimulus of this changing environment may well have led to man's evolution and to the differentiation into the varied races. Man originated, it is said, in Central Asia (Turkestan?) and dispersed in irregular zones all round that continent. The Neanderthaloid type lived in south Asia and gave rise to negroes. The Mindel glaciation drove them out; later they reached Africa. *Pithecanthropus* is also a relic of a bygone type which was pushed to the margin by later forms. The Talgai skull (of Queensland), the Keilor skull (of Melbourne) and the Tartanga skeletons (of South Australia), all of which belong to *Homo sapiens*[537] and may date back

to later stages of the Pleistocene, suggest the existence of palaeolithic man in Australia (see p. 1239).

While the evolution of man may have been polycentric in the Old World (see p. 836) and also it is suggested[538] in the New World, America as a source seems to be excluded; anthropoids and Primates are absent from its Tertiary beds or from the raised beaches with which the Atlantic coast abounds (see ch. XLIV); human remains or artefacts are unknown from beneath deposits of a major glaciation and remains of long-headed *Homo sapiens* alone have yet been discovered—South America has known only a branch of the platyrhines whose phylogenetic history is quite unknown, since save for a single Miocene genus, *Homunculus*, the fossil record of the group does not extend backwards beyond the Pleistocene.

The question of the first peopling of North America has been attacked vigorously in recent years and along many lines. In the first quarter of this century archaeological opinion had crystallised into a doctrine from which there was only mild dissent: that man was a recent invader via the Bering Strait. The discovery of beautifully chipped points at Folsom, Mexico, associated with mammoth and numerous skeletons of an extinct species of bison,[539] brought about a new orientation. Unfortunately, the ambiguity of much of the stratigraphical evidence and of the associations of most of the finds has made it difficult to determine either their age or their place in the cultural sequence.

While evidence of this kind has satisfied several geologists of man's existence in America during the Ice Age[540] it is not extremely trustworthy.[541] Examination has so far failed to reveal any specifically upper palaeolithic types of human implement, though the claim has been made that true palaeoliths occur, from Pre-Chellean to Mousterian. But generally they are rejected since their origin is uncertain and their resemblance to modern Indian artefacts is close. Human skeletal fragments,[542] said to be associated with remains of extinct animals,[543] e.g. mastodont, mammoth, ground sloth, armadillo, glyptodont, sabre-tooth tiger, and extinct species of bison, camel, horse, tapir, musk ox, antelope and deer, and birds and reptiles, were found in beds disturbed by extraneous intrusions from the surface or of questionable age. They may be recent burials, as has been suggested for example for "Florida man".[544]

The Pleistocene animals also provide inconclusive evidence since a few of the typical ones survived in North America to a later geological date than in Europe. Mastodont, for instance, occurs north of the southern limit of the Mankato drift and in post-Pleistocene swamp deposits in Ohio[545] and in post-Whittlesey deposits in south-west Ontario[546]; the mammoth survived (as pollen analysis shows[547]) until *c.* 10,000 years ago and reached its final and most progressive stage of evolution in North America.[548] Dried mummies of *Nothrotherium* are found in southern caves with coprolites which show that this little ground sloth fed on the same vegetation as that which still exists in the neighbourhood[549]—man may have contributed to the extinction of the animals.[550] The preservation of the hair, hide, tendons and horny sheaths of claws also points to the recency of the remains. Thus while the association of extinct animals with human evidence is now established—Folsom points were found beneath the ribs and in the channel of the spinal chord of extinct animals and human representations of mastodont and mammoth have been discovered[551]—the animals themselves are no longer competent witnesses

of antiquity and supplementary proof of age has now to be found elsewhere.

Since C. G. Abbott,[552] from the rude implements found in the gravels overlooking the Delaware River, first maintained in 1872 that early man existed in North America, the question has aroused much discussion.[553] E. B. Renaud[554] has given a map of the localities in dispute and E. H. Sellards[555] an index to these and a selected bibliography. Among the more recent localities (fig. 165) are Folsom, Conkling Cave, Burnet Cave, Sandia Cave and Clovis in New Mexico; Lake Mohave, Pinto Basin and Borax Lake in California; Cochise in Arizona; Abilena and Plainview in Texas; Signal Butte, Scotts bluff and Bison Quarry in Nebraska; Lindenmeier and Yuma in Colorado; Pelican Lake in Minnesota; Gypsum Cave in Nevada; and

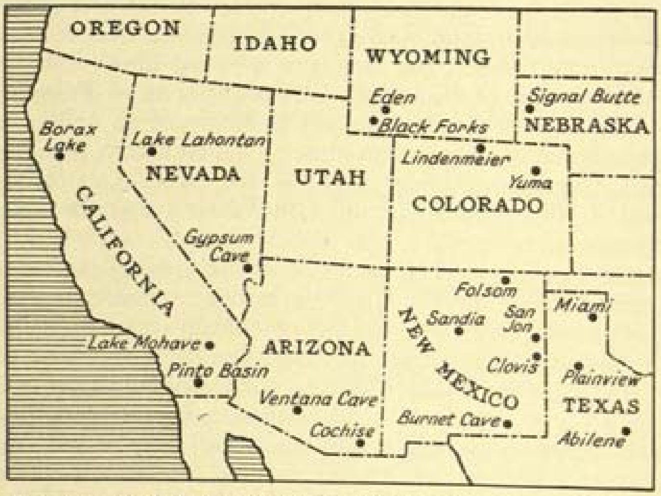

FIG. 165.—Map of the chief prehistoric sites of south-west U.S.A. K. Macgowan, *1901*, p. 115.

Vero-Melbourne in Florida. The geological occurrences include stream terraces, caves, loess, peat and lake-deposits; artefacts have been found in beaches of the proglacial lakes (Lake Algonquin) of Wisconsin age[556] and in the deposits of the Provo-Pluvial of Lake Bonneville,[557] of Lake Lahontan[558] and of Summer Lake.[559]

Hrdlicka,[560] who critically discussed (with full literature) the skeletal remains, concluded that no human bones of undisputed geological antiquity were known—all the human skeletal material falls within the range of recent North American types. A recent date seems indeed to be implied by the verdict of physical anthropology, by a genetic study of the aboriginal Indian populations of North America[561] from the Eskimos in the north-west to the Fuegians in the south, and by the striking fact that not a single cultivated basic food plant was common to the two hemispheres before the close of the 15th century and no domestic animal, except the dog, was common until after the period of European expansion.[562]

Yet evidence, well authenticated, such as soil profiles, suggests that in Florida, Texas, Colorado, Minnesota and other States, extending from the High Plains to nearly the Gulf of Mexico, man (Palaeo-Indian) long

preceded the Basket Maker (who appeared at the beginning of the Christian Era or at earliest in 1000 B.C.) and dates back to lateglacial time or the transition between Palaeolithic and Neolithic,[563] i.e. 10,000–15,000 years ago when peoples of mesolithic status immigrated and the climate in the Great Basin region was moister than now. The Denbigh flint complex,[564] which was discovered in 1948 in Alaska and included blades of generalised Folsom and Yuma types (figs. 166, 167) and a large assortment of burins closely

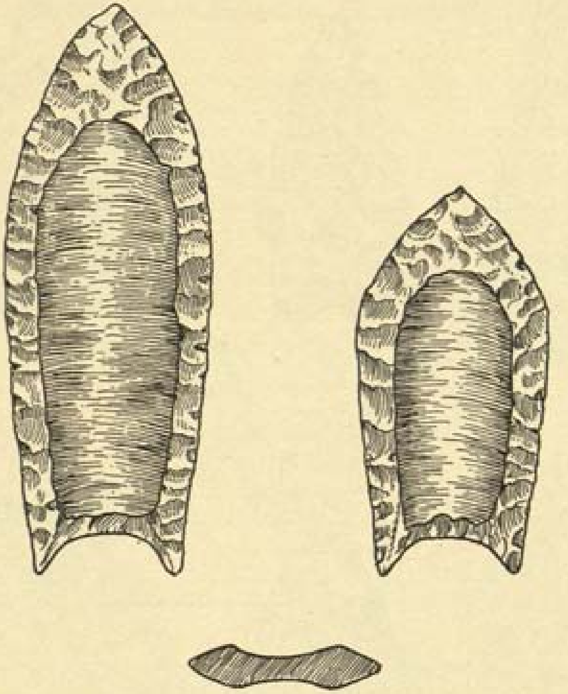

FIG. 166.—Two forms of Folsom points from Lindenmeier, Colorado. H. M. Wormington, *Ancient Man in North America*, 1949, p. 26, fig. 4.

resembling those of upper palaeolithic and mesolithic times in the Old World, links North America with sites in Kamchatka, Manchuria, Mongolia and southern Siberia. These studies have now entered a phase of differentiation of cultural horizons and sequences[565] forming the opening chapters in New World prehistory. There can now be little doubt that man inhabited North America at the end of or during the last glacial or pluvial epoch: archaeology and palaeontology or the contemporary occurrence of mastodont, mammoth, camel, horse and large edentates agree in proving this. Pleistocene man in North America is now therefore established: the only question is how far back his title extends. The radiocarbon method dates the sloth dung, associated with artefacts in Gypsum Cave, Nevada, as *c.* 8500–10,500 years ago[566] and the Folsom remains at about 10,000 years ago.[567] Fluorine tests applied to other human remains are generally confirmative.[568] No trace however has yet been found of human remains differing from those of present man in North America.

Man came from north-east Asia to Alaska along a pathway north of the

Bering Strait proper—the occupation of the Aleutian Islands was relatively late and was westwards from Alaska—and spread to the east of the Mackenzie

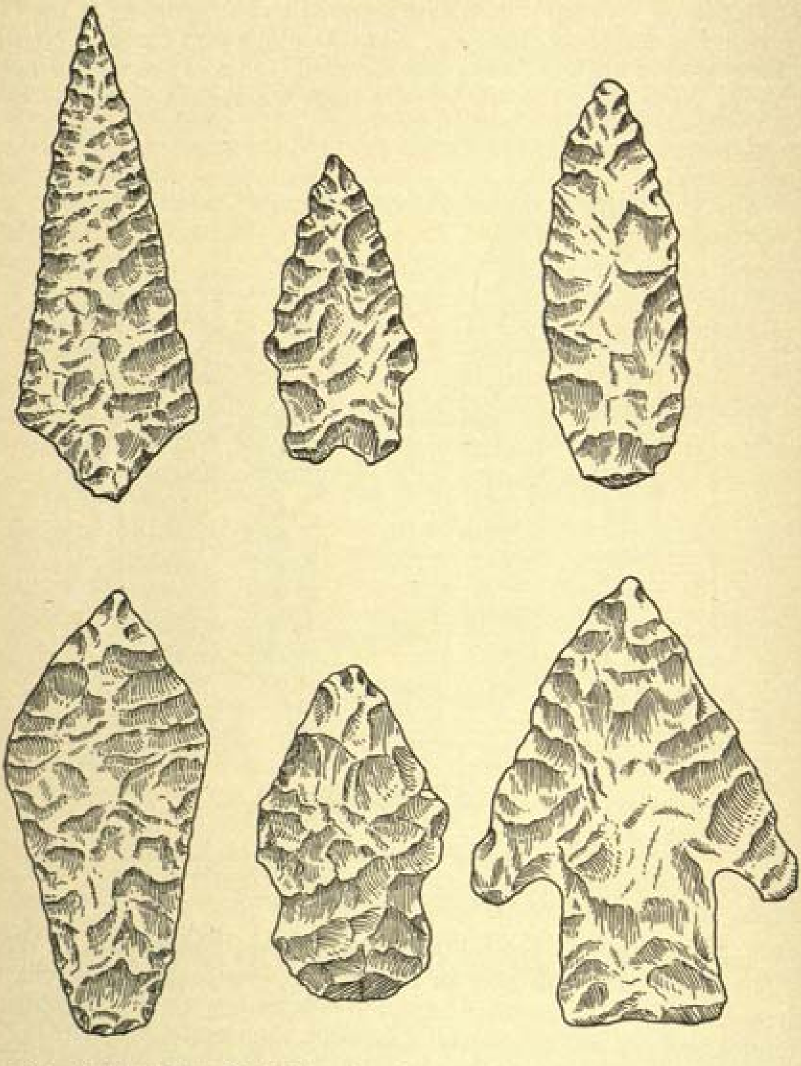

FIG. 167.—Artefacts from North America. Upper row: *left*, Gypsum Cave point; *centre*, Pinto stemmed point; *right*, Pinto leaf-shaped point. Lower row: *left*, Lake Mohave point; *centre*, Silver Lake point; *right*, Borax Lake stemmed point. H. M. Wormington, *Ancient Man in North America*, 1949, p. 79, fig. 17.

(fig. 168) and along the eastern foot of the Rocky Mountains by an ice-free corridor through the Great Plains between the Keewatin and Cordilleran ice[569] (see p. 731): the records are in the form of skeletal remains, dart points, knives, scrapers, etc. This route was continued down the plateau between the Rocky Mountains and the Coast Range and along the Colorado Piedmont into the Great Basin and south California, Arizona and Mexico. Chipped flints in some of the beaches of Lake Agassiz (see p. 475) suggest that man hunted

and fished on the shores of this lake in its later stages.[570] This infiltration via the Bering Strait continued into later times.[571]

A. Penck and others have questioned the possibility of man having become so widely dispersed and having adapted himself to so many different climatic zones in the short time mentioned above. Man, they think, was interglacial too.[572]

The evidence from central and South America is generally negative[573] but here, also, mastodont and other animals survived to the time of man[574] and burnt bone from sloth, horse and guanaco, associated with human bones and

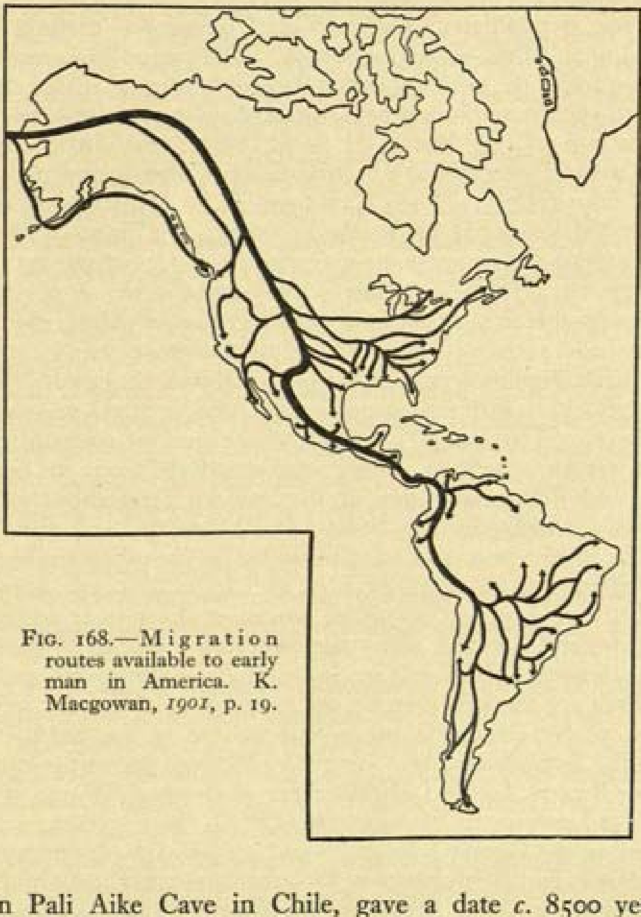

FIG. 168.—Migration routes available to early man in America. K. Macgowan, *1901*, p. 19.

artefacts in Pali Aike Cave in Chile, gave a date *c.* 8500 years ago by radiocarbon.[575] Palaeolithic man, however, has been claimed for this region[576] and even his origin has been placed here.

What became of palaeolithic man? It has often been stated,[577] more particularly in the last century when knowledge of European cultures began to take definite shape, that there was a hiatus between the extinction of the reindeer hunters of the Palaeolithic and the appearance of the new ethnic groups equipped with a neolithic civilisation. Europe was an empty continent. Many facts, it was thought, could bear no other interpretation. Several Pleistocene animals died out at the end of the period; palaeolithic art,

reached after long ages of endeavour and experience, disappeared; the palaeolithic and neolithic layers in caves are sharply separated, often by a sterile layer, and their remains have different states of preservation; the Neolithic did not develop from the Palaeolithic as Lartet and de Mortillet showed; and the Newer Drift is without palaeolithic man.[578] The latter was exterminated by later invaders[579] or perished by glacial submergence[580] or the glacial cold[581] or by both these factors[582] or by the onset of dry steppe conditions which, by providing big animals with insufficient nourishment, left man dependent upon steppe animals for his food.[583]

That no such *ancien hiatus* occurred is now certain,[584] though a hiatus of several thousand years has recently been affirmed for Moravia.[585] Europe, far from being depopulated, was inhabited by several distinct groups of hunting, fishing and food-gathering tribes. The palaeolithic races survived and either fused with the peaceful penetration of new races, under the pressure of dense agricultural populations, or formed the substratum of later peoples.[586] Such a transition—J. A. Brown[587] spoke of a "mesolithic period"—is indicated by several intermediate industrial types, discovered in England by Brown, H. Taylor (King Arthur's Cave) and A. L. Armstrong (Creswell), in the Pyrenees (Mas d'Azil) by E. Piette (1895), in France (Tourasse) by de Mortillet (1896) and in north-west Germany by G. Schwantes (1928) and A. Rust (1937, 1943); by Tardenoisian prototypes in the upper Palaeolithic of the western Mediterranean[588]; and by the survival of palaeolithic industries as at Cissbury and Grimes Graves[589] and of Solutrean in the arrow heads of the European Neolithic and the worked knives of Egypt,[590] of upper palaeolithic influences in the flint cultures (blades, scrapers, burins, shoulder points and awls) of Hamburg[591] and elsewhere, and of palaeolithic races as Neanderthal traces among neolithic and modern man in Spain,[592] of Aurignacian and Solutrean types in the modern populations of Sardinia, north Portugal, Dordogne and Scotland (Rhinns of Galloway[593]), of the Grimaldi type in neolithic and later inhabitants, including those of modern times, of Brittany, south-west France, Switzerland, north Italy and the Balkans and of Cro-Magnon or earlier stocks in the poorer moorlands and places of refuge and isolation along the neolithic types of Wales.[594] Cro-Magnon man retired northwards in Europe before the invading forests[595]: his descendants are the arctic stone age peoples of Denmark and Scandinavia[596] (see p. 877) and the megalithic people of the north,[597] and his relatives are the Laplanders.[598] The type is likewise present in the people of the Neolithic, Bronze Age and Middle Ages of Germany[599] and is now to be seen among the Libyans, in Biscayan Spain,[600] in the Dordogne valleys,[601] in the Guanchos on the Canary Islands,[602] and in Germany (Westphalia, Hesse), Sweden (Dalarne) and north Norway.[603] A likeness to the Grimaldi type[604] is to be observed in North Africa, Wales, France (Rhône Valley) and north Italy. The western European alpines may be upper palaeolithic survivors, somewhat reduced in head and face size.[605]

Unquestionably, therefore, new cultural elements have been grafted on to the expiring palaeolithic stem and some of the inhabitants of Europe have drawn in their descent upon upper palaeolithic stocks.

Palaeolithic man, it has often been contended, has scattered to the extreme corners of the globe.[606] The Chancelade race is the Eskimo of to-day (see p. 861). Mousterian man survives in the Tasmanian and Australian aborigines[607] (see p. 864)—the last aboriginal Tasmanian died in A.D. 1876—

whose industry,[608] though specifically distinct from the Mousterian, is closely related to the industry in west Spain. The problem of the antiquity of man in Australia is still unsolved.[609] The Australian aboriginal may have arrived (with the dingo) in Australia in late Pleistocene[610]; alternately, he is linked, through the stages of Talgai skull, *Homo wadjakensis* and *Javanthropus soloensis*, with *Pithecanthropus*.[611]

The South African bushman was similarly descended from *Homo rhodesiensis*[612] (and *Africanthropus njarasensis*) or from Aurignacian and Solutrean man[613] because of his physical characters and his industry and art.[614] The cave art, which betrays in its social structure, method of working of stone and artistic and physical features a striking likeness in the caves of Spain to that of the bushmen[615] or the earlier series of paintings in Southern Rhodesia, has been followed across Africa from north to south,[616] e.g. North Africa, Sudan, Sahara, Chad states and Transvaal. The rock-engravings of North Africa,[617] which are found in groups in the open and near old river beds and spread into east Spain,[618] belong for the most part to the "neolithic" (see below) and younger periods, parallel in age to pre-dynastic and dynastic Egypt. Some may date from the upper Palaeolithic—at only one site in Africa has it been possible to establish a parallel between archaeological groups and wall paintings. Their leading motifs are animal and human forms and especially the weapons and clothing of man. The engravings, which are bounded by deep, smooth polished lines and may have been painted, ended in extreme conventional designs.

The earliest of the three series recognised by H. Breuil[619] on technical and physical grounds is assigned by him to the upper Palaeolithic but because of the increasing aridity of North Africa at that time (see p. 1129) has been referred to the postpluvial "neolithic period"[620] (see p. 1488). The paintings of South Africa[621] are recent but may range backward in time to 10,000 years ago.

That the bushmen came from North Africa[622] is suggested by the "negroid" skeletons of Grimaldi (these, it has been said,[623] may not be negroid but a southern variant of the Cro-Magnon stock); by a fossil skull (Singa) of an ancestral bushman from the Anglo-Egyptian Sudan,[624] with implements of Levallois technique; and by the figurines of Grimaldi, Brassempouy, Lespaugue and Willendorf, the bas-reliefs of Laussel, and the rock-paintings and engravings which extend through Africa (see above), as in Egypt[625] (including paintings of giraffe and ostrich), and become later in age as the south is approached. The Springbok type of northern Transvaal may represent a negroid type which migrated southwards during Aurignacian time.[626] The Hottentot, instead of being a Bushman-Bantu, as has been generally held, may be the product of an evolution from a "Wilton race"[627] which (contemporaneous with the Smithfield industry of the Orange Free State), as is usually recognised, has strong affinities with late-palaeolithic man in Europe and North Africa. Others regard South Africa as the evolutionary cradle of the Bushman[628] who wandered northwards through Africa into Europe[629] and left traces in the pre-dynastic peoples of Egypt.[630] Others again think east Africa was his home,[631] or that Bushman and Aurignacian man descended from a common stock.[632] The Bushman problem is obviously still unsolved.

Yet a connexion between palaeolithic man and modern primitive peoples is often denied[633]; the resemblances are cultural rather than racial (cultural

identity does not imply racial identity) and of a functional kind, arising from similar conditions or from atavism or reversion. Nevertheless, the attempt to explain physical and cultural resemblances in this way appears to be inadequate. But we can only be sure about the origin of modern races when the discoveries of fossil man are sufficiently numerous in space and time to permit us to map the distribution of mankind at every phase.

3. *Mesolithic Man*

The changed environment associated with the passing away of glacial conditions—the contracting ice-sheets, the replacement of tundra and steppe by forest in North Europe and the progressive desiccation of North Africa and the Near East—gave rise to a new civilisation. While Europe was never empty, there was a real break in historical continuity: agriculture, pottery and polished stone tools were introduced by new peoples.

The mesolithic period, which formed the earlier part of the "neolithic" period used in its very wide original sense, embraces the Ancylus period and part of the Littorina period up to the Ertebölle period.[634] It is sometimes divided into epipalaeolithic below and proto-neolithic above, the former comprising the Azilian and Tardenoisian. As these cultures were probably descended from the palaeolithic and restricted to Europe (epipalaeolithic types are unknown east of the Urals) and are distinct from the neolithic waves that proceeded from the east, they have all been grouped in the epipalaeolithic.[635]

The environment of these peoples was the primaeval forest which now replaced the tundras (see ch. XLVIII)—the birds of the Azilian station of Birseck near Basle were those of the woods and fields of the region to-day,[636] as was the vertebrate fauna of the early Tardenoisian Günzberg in Switzerland.[637] It demanded the adoption of tools of horn, bone or stone which the wood worker could employ as adzes, chisels and perhaps axes. Corn was grown since remains have been found in western Europe[638] and flint sickles of mesolithic age are known for Palestine,[639] and wooden ploughs of the oak-hazel period for Germany.[640] Domestication began much later. The domestic dog is first known in the English Azilian and in Portuguese and Danish (Maglemose) kitchen-middens,[641] though H. Martin[642] asserted that Mousterian man hunted with dog (= wolf). The domestic horse is rare in Europe before the Bronze Age[643]: it was absent for example from British long barrows, from the Danish kitchen-middens and from the Swiss lake-dwellings.[644] Cattle, pig, sheep, goat and dog in the Swiss lake-dwellings[645] (see p. 883) point to domestication (dog was not domesticated in the older neolithic pile dwellings[646]), while red deer, fallow deer, roe deer, elk, brown bear, aurochs, fox, hare, chamois, wild duck, stork, swan, heron, pike, salmon and carp show that hunting and fishing were also practised. Elk abounded in the Boreal period, with its willow and birch, and red deer, with roe deer and wild pig, during the mixed oak forest. Barley, wheat, oats, rye and millet, with querns and sickles, confirm the existence of agriculture. Wild fruits (plum, sloe, cherry, raspberry and strawberry) were collected.

The mesolithic peoples of Britain made shell-middens as on Oronsay and hearths as on the Pennines, inhabited caves, such as Victoria Cave, Settle, and Mother Grundy's Parlour, Creswell, and had settlements of pit-dwellings as at Selmeston, Sussex.[647]

The chief mesolithic cultures are the Azilian, Tardenoisian and Asturian in southern Europe, and the Maglemosian, Campignian and kitchen-middens of the north of the continent.

Azilian. The Azilian, found in the first instance by Piette[648] in the cave of Mas d'Azil—de Mortillet's Tourassien of the shelter of La Tourasse[649] (Haute-Garonne) was its contemporary—had rudely chipped flint implements which embraced small round scrapers without trapezoid and geometrical forms. The "type fossil" was the double-barbed, flat harpoon of red deer antler which was broader and flatter than the traditional Magdalenian type. It was of two kinds, the one with unilateral barbs and oval perforation, the other with bilateral barbs and round perforation. Additional tools included bone polishers, spatulae and rough bone awls.

The finished realistic Magdalenian art, with its decoration of bone tools

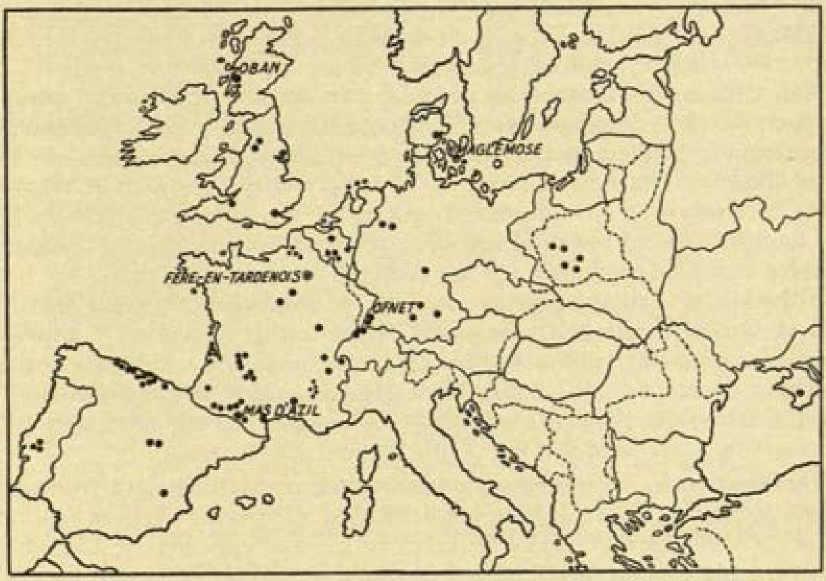

FIG. 169.—Map showing the distribution in Europe of the Azilian, Tardenoisian and Maglemose cultures. G. C. McCurdy, *1051*, II, p. 16, fig. 262.

and harpoons, its animal engraving and its sculpture, has vanished. It has been replaced by schematised and conventional designs smeared in ochre on cave-walls, and by painted pebbles. The red spots, bars, curves and circles of these *galets coloriés*[650] of Mas d'Azil, north Spain, Pyrenees, east France and the country as far east as Birseck near Basle,[651] have an unknown motive; they may be talismans or means of counting, have religious significance, or represent a conventionalised human form. More probably, they are magic objects, indicating by their replacement of the true portrayal of the upper palaeolithic art by a symbol, a rising human intelligence.[652]

The Azilian people, snail eaters and hunters of stags and wild boars, lived in shelters or at the mouths of caves over a wide region[653] (fig. 169), including the Pyrenees, north Spain, Dordogne, east France—a mixed Azilio-Tardenoisian industry is found in Switzerland[654]—Bavaria and Liège and in Croatia and Caucasian and Crimean caves.[655] Anomalous finds, which

belong to a people probably extremely few numerically, have been recorded from the British Isles[656]; e.g. several points on the coast, e.g. Whitburn (Durham), Inchkeith (Edinburgh), Bute, Colonsay and Oronsay, stray finds in the bed of the River Dee (Kirkcudbrightshire) and River Irvine (Ayrshire), and the harpoon at Victoria Cave, Settle. They also include bone and horn implements, e.g. pins, awls and harpoons, found with hearths and kitchen-middens and human remains in the raised beach cave at Oban[657] which was apparently occupied when the sea still had access to it. These Azilian implements,[658] larger than those in France or Spain and made of bone instead of deer antler, had close affinities with the Maglemose of Denmark[659] whence the families may have reached Scotland by crossing the Midland Valley. This Obanian, as it has been called,[660] appears to have come from the south via the west coast and to be a late survival (late Atlantic)—it is later than the Larnian and probably early Neolithic.[661] The Victoria Cave harpoon which is made of reindeer and typologically older probably preceded the Obanian. Obanian has also been found on the island of Risga in Loch Sunart[662] where it is probably early Neolithic.

The Oronsay shell-mounds, which are specifically Azilian and contain a harpoon which in Sjaelland dates from just before the Littorina maximum, are later than the Maglemose (of Ancylus age) and roughly coeval with the Baltic Ertebölle.[663] The flint implements in the 25-ft raised beach at Campbeltown,[664] Kintyre, which are heavily patinated and belong to the Mesolithic, are founded upon upper palaeolithic (Creswellian) survivals. The painted pebbles at Keiss, Caithness, are not Azilian.[665]

Although the Azilian's position above the Magdalenian is fixed at Mas d'Azil and at Ofnet[666] (Bavaria), its origin is somewhat obscure. Culture and people may have arrived in Europe from the south and south-east but more probably developed in Cantabria from the degenerating Magdalenian[667] as the flat harpoons show. Their skeleton remains have been found in few places,[668] namely at Mas d'Azil and at Montardit (Ariège).

Tardenoisian. Tardenoisian man gathered shell-fish and hunted and fished along the shore. His microliths, first discovered at Fère-en-Tardenois[669] (Aisne), are generally found at or close to the surface, though man occupied natural shelters where these were available,[670] e.g. at Ensdorf in Bavaria (Franconia) and in numerous localities in Belgium (e.g. the grottos at Zonhoven and Remouchamps; see p. 855). The pigmy splinters, about 3 cm long, are generally chipped into geometrical shapes, e.g. triangles, crescents, lunates and (later) trapezes. They were probably mounted in straight rows in wooden handles (which because the sites were sandy are nowhere preserved) and used for tattooing—analogous forms are being made to-day[671]—or, more probably, for fishing, as hooks or harpoon barbs, such as are now used by primitive peoples in west Africa.[672] This is made probable by the find of a bone sickle shaft from the Natufian of Palestine with two flint flakes still in place[673] and is established by the discovery of a straight line of microliths spaced at regular intervals of *c.* 5 cm in the peat-covered sand in the Pennines, the containing shaft having rotted away.[674] The composite tools also served as arrow-heads, saws, fish-hooks, cutting tools, borers and the like.

Lower Tardenoisian is marked by non-geometrical points and microburins, middle Tardenoisian by microburins and geometrical forms, upper Tardenoisian by geometrical forms, few trapezes and rare microburins, and late Tardenoisian by abundant trapezes.

Pigmy implements (which also occurred sparingly throughout the Palaeolithic,[675] especially among its later cultures) are found as far east as the Crimea, Poland[676]—this Swiderian (see p. 878) or "Chwalibogowician" of the lowest levels of the sand dunes which extends from the Black Sea to the Baltic is characterised by a small shoulder point—and the Ukraine, and are widespread around the Mediterranean and on coastal sites or open camping spaces in west Europe (fig. 170), e.g. Belgium and Britain[677] where besides the sites mentioned below, they inhabited the sandy margins of the East Anglian fens, sand dunes in Lincolnshire, and the coasts of Cornwall, Devon, Wales, Isle of Man, and Scotland from the south-west to Caithness and the Orkney Islands in the north-east. They arrived late; they are Boreal in the

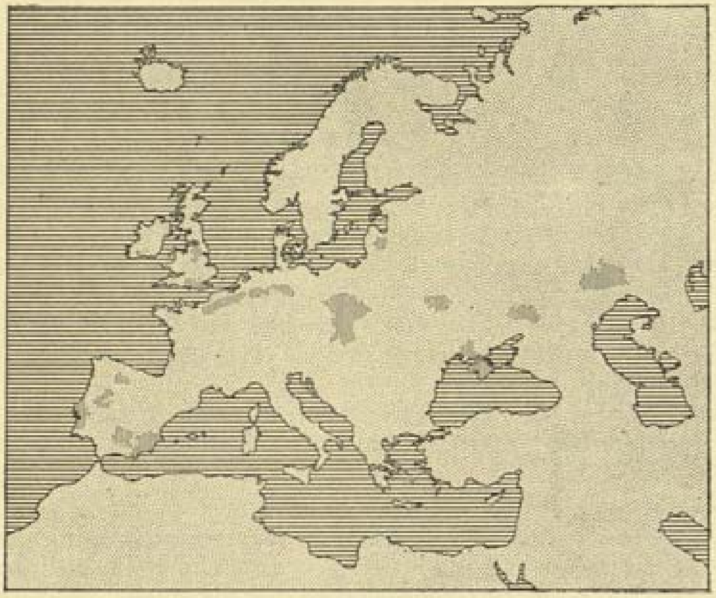

FIG. 170.—Map showing the distribution of the Tardenoisian industry in Europe. H. Peake and H. J. Fleure, *1267*, p. 147.

Pennines, uppermost Boreal or lower Atlantic[678] at the coast, e.g. in north-east England, and late-Atlantic[679] in west Scotland.

Similar implements of uncertain age have been traced through Africa from Egypt to Cape Blanco and from north Tunisia to Lake Chad, Kenya, Rhodesia and the south (= Wilton industry), as well as in India and Australia.[680] A neolithic people who made small artefacts, especially arrow heads and scrapers, lived on the banks and shores of North Siberian water-basins.[681]

The European sites were situated often on exposed rocky uplands, e.g. the Pennines and the limestone cliffs of Durham,[682] occasionally in rock-shelters[683] (see above), and more characteristically in round or oval pit-dwellings[684] in sandy soils, e.g. fossil dunes associated with the North German *Urstromtäler*, and at Federsee (Württemberg) and Ansbach (Bavaria). They avoided the loess of the south and the northern forests inhabited by Maglemose man; and they lacked the axes, adzes and picks, etc., of flint or

bone to cope with the forest and the agricultural equipment, including pottery, necessary for cultivating the loess.[685]

The true Tardenoisian was associated with a forest fauna—at Creswell, this comprised horse, pig, bison and red deer. It was contemporaneous with the Azilian; for example, in the cave of Valle, near Gibaja, Tardenoisian finds are associated with Azilian tools including harpoons.[686] It was revived from Mediterranean sources,[687] either from the Capsian (the final Capsian, coeval with the French Tardenoisian, gave rise by mixing to the Capsio-Tardenoisian) or the latest Aurignacian,[688] as in the Grotte des Enfants (Mentone) and about Sulaimani (north-east of Bagdad) where the Aurignacian culture continues upwards into undisturbed Tardenoisian uninfluenced by Solutrean or Magdalenian. In north England, it was preceded by the developed Aurignacian, styled Creswellian.[689] The microburin or "type fossil" of the Tardenoisian found in Magdalenian stations proves that these two cultures, though cradled in different environments, were contemporaneous.[690]

The Azilian-Tardenoisian cultures have been associated with new races, the dolichocephalic Ofnet race (33 skulls were found at Ofnet[691]) and the brachicephalic Furfooz-Grenelle race of France[692]: the Ofnet type is represented in England[693] at Aveline's Hole (Mendips) and in Kent's Cavern, Torquay. They may, however, have been evolved by Aurignacian peoples who during the Solutrean domination retreated to the Pyrenees and other mountains (where for lack of flint they developed an industry of bone and horn) or from the population of North Africa, Palestine and Syria which overflowed via the Strait of Gibraltar in the west and the Black and Caspian Seas in the east, with the progressive desiccation that marked the end of the Pleistocene[694] (see p. 1410).

The Tardenoisian has been correlated with northern industries as follows[695]: Tardenoisian, Lyngby; Tardenoisian II, Maglemose; Tardenoisian III, Ertebölle.

Fosna culture. The early human cultures of Scandinavia, which have received very careful study,[696] are dated by their relationship to postglacial sea-levels, by pollen analysis and by the associated fauna. Round the Baltic the successive stages in the colonisation of the North, the development of wood-working tools and the adjustment of general economy, correlated with the changing sea-levels and with climatic phases, are fully documented in the Hamburg, Lyngby, Maglemose and Ertebölle cultures.

The oldest dwelling places in Sweden occur near Göteborg (Sandarne, Gottskär, Råö) and near Varberg. Earlier than the Littorina transgression, they probably belong to the Yoldia period.

Other early evidence of man's occupation comes from a series of open-air sites, marked by an occasional fire-place, along the Norwegian coast between Bergen and Trondheim which, typologically reminiscent of the late palaeolithic, have been equated with the Magdalenian farther south.[697] The industry consists of gravers, microliths, picks, axes, adzes and tranchets made, in the absence of flint, from schist, quartz and igneous rocks. The primitive flint picks and other implements of this Fosna culture (from Fosna at the outlet of the Trondheimsfjord) occur in the region of Kristiansund at 40 m (= 19 m above the Tapes level) and extend northwards from Bergen to north of Trondheim in a series of stations or *flint-pladsene*[698] situated in sheltered landing places. They are also found in south-east Norway and as far south as Bohuslän and Halland in Sweden[699] but are probably absent from Den-

mark because the sea at that time (Ancylus age or slightly earlier[700]) lay farther west.[701]

Finnmark or Komsa culture. Palaeolithic peoples, it is claimed, lived on the Arctic and Atlantic seaboard of Fennoscandia[702]; true palaeoliths, it is said, occur in south Norway[703] (Chellean), and with musk ox and mammoth, in Finland and south Sweden[704] (Solutrean). Types ranging from Mousterian to Magdalenian[705] are also said to be included in the Finnmarkian or Komsa culture[706] (named from a mountain in the Altafjord): they were based upon "Mousterian" types and gradually enriched by Aurignacian and Magdalenian influences. The flakes and cores suggest connexions with Siberian and Chinese palaeolithic cultures.[707] Sandarna near Gothenburg has forms characteristic of this culture.[708] The raw material of the industry, which was coastal between Kattegat and Varangerfjord, was a red-brown quartzite and a "dolomite-flint" of Eocambrian age but mostly derived from moraines. The Finnmarkians may have been adapted to cold conditions, flourishing on seals, whales, fish, polar bears and sea-birds: when the temperature rose and the pack-ice and seals withdrew the culture came to an end.[709]

Arctic stone age. The "arctic stone age" of north Scandinavia,[710] based on a lithic industry in slate, quartz, quartzite and schist, including a rich variety of arrow heads, spear heads, knives and daggers of original form and technique, succeeded the Nøstvet culture (see below) with which it has transitions. Though possessing direct contacts with the megalithic and battle-axe cultures, it had roots in a still earlier epipalaeolithic bone industry,[711] traceable from south Norway to 69° N., as its naturalistic paintings of reindeer, elk, sea-birds, whales and fish testify[712]—there is a hint that hunters sharing these artistic traditions reached Scotland.[713] The discovery that the industry spread southwards along the Norwegian coasts in south Sweden and Gotland made untenable the earlier view (1874) of O. Rygh and O. Montelius[714] that the industry was an autochtonous Lapp stone age culture. Amber and other objects prove a direct connexion with the Baltic region. The arctic stone age, which seemingly coincided with the coniferous forest,[715] also extended into Kola Peninsula[716] and arctic Russia[717] and was apparently part of a circumpolar stone age[718] which even expanded into North America.

Age of Scandinavian cultures. A. Björn,[719] who denies the palaeolithic age of these cultures, links them with the Nøstvet culture (see below). He postulates a north–south migration through Scandinavia in Pre-boreal time and derives the Nøstvet from the Fosna culture and this in turn from the east through the more primitive looking but closely connected Finnmarkian. This characterised open country far above present sea level and was connected right across Russia with Siberia where the upper Palaeolithic contains harpoons and other bone implements as well as flint and some types comparable to Komsa forms.[720]

The Fosna and Komsa cultures, however, have proved difficult to date since the contemporary fauna or flora have left no trace. The tangled points and burins suggest affinities with the upper Palaeolithic and especially with the earlier mesolithic culture that extended from Belgium to the Ukraine. Bromme is ancestral to Komsa and Fosna,[721] as is the Swiderian[722]: Komsa-Fosna may also be descendants of the Pinnberg-Lyngby hunters[723] which in turn may have been derived from Meiendorf.[724] The flake industry of Ahrensburg-Lavenstedt,[725] of Pre-boreal age, with its blade and

flake implements and characteristic tanged point or microlith (reproduced almost completely at the Belgian cave of Remouchamps near Spa) resembles the Swiderian (type locality, Swidry) or Chwalibogowician (see p. 875) of the valleys of the Vistula and the Bug, the roots of which go back to the loess man of Aurignacian or Předmost facies.[726] In the cave of Hohle Stein, Westphalia, its industry is associated with a transitional fauna including species of both tundra (reindeer, arctic hare, arctic fox and white grouse) and forest (red deer, roe deer, elk, boar, beaver). The Hamburg fowlers and hunters—their implements were harpoons and bows and arrows tipped with bone or asymmetrical flint points—were summer visitors only; they followed the reindeer northwards on their seasonal migrations but dwelt for most of the year farther south,[727] e.g. in Holland, Swabia and East Prussia: reindeer antlers cut with characteristic grooves occur here. Probably the earliest of the mesolithic industries, and belonging to the same time as the Lyngby,[728] it was later supplanted by the axe culture of the Tardenoisian. The discovery of Komsa artefacts in beds of Boreal or Ancylus age proves that, though of palaeolithic aspect, their age is much younger[729]: it is Mesolithic and lies between the Portlandia strand (Tanner's Ic) and the Tapes strand[730] (Tanner's IIa). The Fosna culture belongs to the early Ancylus or later and may have extended upwards into the Neolithic.[731]

Axe-like tools of reindeer antler, shaped like a hoe and resembling those found in Posen, Brandenburg, Holstein and the Rhine region, have been discovered in Denmark[732] and at Nörre-Lyngby[733] in association with a sub-arctic fauna[734] and probably the first growth of forest and with a flint arrow head or simple triangular blade like those which later occurred in Kristiansund. Rock-engravings in three localities in Jämtland and in other places in Norway, with naturalistic representation of elk, bear and reindeer, may belong here.

Campignian. The proto-neolithic peoples, the Campignian, Kitchen-midden and Nøstvet cultures, were coastal in the main like the epipalaeolithic. The climate was moist—the moisture-loving snail, *Helix nemoralis*, lived at Mas d'Azil—and forests advanced over much of Europe, as in the Scottish Azilian[735] and the basin of the upper Danube,[736] and prevented the peoples from penetrating far inland,[737] though neolithic man cleared the forests by burning[738] as well as by axes and by the grazing of domestic animals[739] (swine, deer, sheep, etc.).

The Campignian implements—the type station is Campigny (Lower Seine) —consisted of the Campigny pick (used possibly to dig up edible roots), Campigny unpolished hatchet (*grand-tranchet*), and rough-hewn hammer or axe-head, with rough awls and scrapers. Polished implements were rare and pottery was absent. Burials of this time are not known.

The Campignian is widespread and invaded Europe from Asia in a series of more or less distinct waves. Absent in the gap between Belgium and Denmark because of later subsidence (see p. 1266) it is found in Belgium, north France, Italy (forming the amalgam with the upper Palaeolithic termed "Garganian"[740]), Switzerland,[741] England (Essex) and north Ireland[742] (25-ft raised beach, Larne), north Germany[743] (Holstein, Mecklenburg, Pomerania), Scandinavia[744] (kitchen-middens of the Tapes-Littorina Sea) and in Volhynia, Lithuania, Poland and Russia. Of the age of the maximum Littorina submergence,[745] as first discovered in Denmark in 1889 by C. G. J. Petersen, it ran parallel with the Ertebölle culture (see below) but ranged

upwards possibly into the copper age in Italy[746] and into the iron age in the Department of Yonne.[747] Even at the type station it is not epipalaeolithic; for the occupants of the pit-dwellings already tamed animals, tilled the soil, and made pots with handles and geometrical decorations. Its polished celts are apparently merely survivals into the Neolithic.[748]

Maglemose or Mullerup. The best-known cultural phase of the Baltic region has been described from Maglemose[749] ("great bog") in Sjaelland; other Sjaelland localities[750] are Svaerdborg, Vordingborg, Holmegaard and Lundby. This lake civilisation, with hunting and fishing as the main occupations—a fishing net has been found near Viborg,[751] Finland—belonged to the Boreal pine forest of Ancylus age (see below) and was surrounded by a rich lake and forest fauna of elk, roe deer, red deer, aurochs, wild boar, wolf, with otter, beaver, badger, martin, wild cat, squirrel, porcupine and marsh tortoise: dog was the only domestic animal. The birds[752] comprised eagle, heron, crane, swan, grouse, grey goose, duck and cormorant. Maglemose man fished pike—pike remains also occurred at the lateglacial levels of Meiendorf and Stellmoor and in East Prussia[753]—and fowled duck, goose and swan; hunted elk, aurochs and pig; and collected wild plants and nuts, berries, seeds (*Trapa natans*, *Nuphar lutea*) and other natural fruits. He built large fires, proved by the charcoal of lime, hazel, alder, birch and elm and burnt bones and calcined flints. His implements were scrapers, picks, adzes, daggers, chisels, fish-hooks and microliths of flint for arming harpoons—the larger flint implements were the pick-axe (*pic*) and flake-axe (*tranchet*), bone implements, chiefly of stag, with elk, roebuck and wild ox and the "type fossil" of small, narrow bone points or harpoons, barbed on one side and often ornamented with line and geometrical patterns. These were unlike the naturalistic decoration current in the upper Palaeolithic of France but strikingly like the Capsio-Tardenoisian[754] (see p. 851). Parallels from Eskimo material make it certain that they were used not as true harpoons but as fish spears and bird catchers.[755]

These people also made axes and adzes with sleeves, or perforated hafts of deer's horn which gave a greatly extended command over Nature. While they sculptured animals on amber[756] they left behind neither pottery nor polished axes nor any indications that they practised agriculture. Wooden paddles from Duvensee and Holmegaard imply the use of boats, either skin-covered or dug-outs.

A human skeleton and jaw,[757] the first Danish human remains, and other osteological material[758] give evidence of the physical characters of the race which appear to correspond to those of Cro-Magnon man or to fall within the variations of the present Europeans.[759]

These settlements, whose very limited extent suggests small social groups, were generally situated on low ground, as fens and rivers, or on the shores or islands of large lakes or lagoons, or, as at Maglemose itself, on a raft-like platform of wood. Like the Hamburgians (see p. 880), who hunted reindeer and camped by pools and lakes in the *tunneltäler*, they occupied these sites as summer camping places only.[760] That they belonged to the middle of the Ancylus or Boreal period[761] and preceded the kitchen-middens is shown by their fauna, e.g. the mollusca (= zone of *Bythynia tentaculata-Planorbis stroemi*), and by the flora, including the pollen[762] analyses (the charcoal gave 72 % of pine at Holmegaard and 80·8 % at Mullerup), and by the absence or

unimportance of oak. Moreover, the horizon occurs below the Littorina deposits in Kiel Bay.[763]

That forests largely determined the environment is reflected in the extensive use of wood for handles, hafts, clubs, javelins, paddle-rudders and dug-out canoes and of axes, adzes, etc., to deal with it.[764] *Emys orbicularis, Planorbis corneus* and *Naias marina* suggest that the summers were at least as warm as now.

The culture is merely a specialised variant, peculiar to Sjaelland, of a more generalised culture which, with the lowered sea-level of the time, spread readily along the coasts of the Ancylus Lake and North Sea from Co. Durham to the Thames,[765] e.g. Hartlepool, Scarborough (Seamer). Holderness, Cambridgeshire (Royston), Hertfordshire (Broxbourne) and the moorlog[766] (see p. 1231). The associated flint implements are widespread in north Europe[767] as far west as the Southampton Water area and Kent's Cavern[768] and as far north as Norway[769] and Sweden (near Göteborg) and in isolated localities over the North German Plain and up the Elbe and Vistula[770] into Poland, Russia and the Ukraine[771] and southwards into Belgium[772] and France.[773] Duvensee[774] near Lübeck is possibly an earlier facies. The tradition survived into the Neolithic in many parts of Scandinavia, either pure or mixed with newer cultural forms.

This civilisation, forced to retire by the Littorina submergence and the advent of forests, has been thought, in the absence of skeletal material, to have been derived from Asian sources[775] (primarily because brachycephals from palaeolithic Europe and North Africa are completely lacking), from a late form of the Aurignacian which survived in south Poland or central Europe into Magdalenian time[776] or, particularly as concerns the introduction of the axe and the short-headed element into north Europe, from the Lyngby culture.[777] Nørre Lyngby, the type locality, is at the extreme northern end of Jutland (Vendsyssel) and had a mixed tundra and forest fauna and a flora (Younger Dryas period) which included such tundra species as *Dryas octopetala, Betula nana* and *Salix polaris*. This culture had a point—the Lyngby point—which was a symmetrical tanged arrow-head better named after Bromme, the Sjaelland site where it was first recognised (see p. 1436); the implement was made of reindeer horn in which the tines have been broken off and roughly fashioned as a blade or hammer-head. These Lyngby or Ahrensburg reindeer "axes", found also in south Norway, Jutland, Fyn, Sjaelland and north Germany[778] (Holstein, Westphalia, Brandenburg, East Prussia), east of the Baltic and as far east as Siberia, were not created in north Germany in Pre-boreal time but were introduced from the south-east where they had been in use during the upper Pleistocene[779] (Solutrean and Magdalenian).

Excavations at Meiendorf, which lay in a tunnel valley underlain by dead ice, and at Stellmoor (Ahrensburg) near Hamburg[780] definitely link the Maglemose forest culture with the upper palaeolithic tundra: the bone and flint implements were associated with pollen indicating the early phase (Ia) of Dryas time. The Maglemose was probably descended by way of north Germany from the Magdalenian, as is suggested by the barbed harpoons, fish-spears, chisels of horn and bone and the survivals of palaeolithic art in the character of the ornamentation.[781] It probably included elements of Magdalenian, Tardenoisian and Campignian[782]—a parallelism with the Azilio-Tardenoisian has frequently been stressed.[783] Its micro-

lithic element, like that of the Ertebölle, was clearly borrowed from the Tardenoisian.

The Kunda antiquities of Estonia[784] contain forms most strongly resembling Maglemose types together with new ones, viz, arrow heads with circular or triangular cross-sections and oblique-edged, pointed implements. They are Boreal, as pollen analyses prove,[785] and represent an eastern development of the Mullerup culture which originated in East Prussia and the adjoining regions and extended into south Finland[786] where they were partly contemporaneous with and partly succeeded by the stone "Suomusjärvi culture" with primitive, slightly ground axes, found on either side of the Gulf of Finland.

The lake-dwellings of Holderness[787] and Berkshire[788] are to be attributed to survivors of the Maglemose in the same way that those of Switzerland[789] exhibit many traits inherited from the Magdalenian and Azilian cultures.[790] The culture also survived in a relatively pure form into Littorina times in south-west Norway (Bergen and Viste near Stavanger) and into the passage grave period.[791]

Kitchen-middens. The Mullerup culture was followed by the kitchen-middens[792] (Dan. *kjökken-möddinger*) or shell-mounds of Denmark and Jaeren in south Norway: the transition is at Braband in Jutland[793] and the type locality at Ertebölle in Denmark.[794] Oak forests came right down to the sea-shore so that the Ertebölle folk remained forest-tribes, and grass or park-land forms were few among the animals—the Gudenaa culture[795] existed contemporaneously in the inland districts of Jutland. The occupations of the people were hooking and spearing fish, hunting with arrow, trapping, and catching birds: seal hunting was indulged in in both Ancylus and Littorina times.[796] Their food consisted of the common edible shells, e.g. oysters (*Ostrea edulis*), cockles (*Cardium edule*), mussels (*Mytilus edule*), periwinkles (*Littorina litorea*) and *Nassa reticulata*, which the warm waters made abundant, of fish (herring and cod) and of the flesh of sea-birds (auks, cormorants, gannets, gulls and swans) and animals. The vertebrate fauna comprised stag, roebuck, pig, bear, wolf, beaver, wild cat, sheep, deer, *Bos primigenius* and seal. Dog, the sole domestic animal, consisted of a small race, *Canis palustris ladogensis*, and a large race, *C. inostranzewi*,[797] which extend backwards into Azilian time in the Baltic region. The small race, of which the *C. palustris* of the Swiss lake-dwellings is a smaller descendant,[798] may have descended from a jackal,[799] from a small wolf,[800] or from some extinct species resembling the dingo that lived in Eurasia[801] (see below).

The implements associated with the shell-mounds, which frequently stretch along the contemporary shore-line for over 100 m, were made of bone, such as stag's antlers, and included awls and chisels and similar small and simple articles and occasional barbed bone points that probably continue unbroken the Maglemose and even Magdalenian tradition.[802] Flint microliths disappeared entirely save for the triangular hatchets and chipped, occasionally polished celts and transverse-edged arrow heads which abounded and the *Skivespalter*. The stone types show a continuity with the Maglemose as well as new departures. These included the technical use of basalt, gneiss, granite and porphyry which were ground.

Coarse hand-made earthenware vessels, small bowls (used as blubber lamps[803]), and deep "comb" pots are found in the later levels of the mounds,

together with layers of charcoal and old hearths of flat, burnt stones. The pottery, with its bone combs and bracelets, is an important new feature. It probably represents a new cultural borrowing from the first dolmen builders[804] or the neolithic immigrants moving in from western Europe or the Danube valley.

The kitchen-midden people, of whose physical features we are almost quite ignorant,[805] were distributed along the open coast during the maximum Littorina submergence, deriving their sustenance from its abundant food supplies, including oyster banks. They also occupied sheltered valleys running inland from it and the shores of inland lakes, living in these places all the year round.[806] Besides Denmark,[807] where they were first discovered, they occurred along the west coast of Sweden from Scania northwards[808] (greenstone is often used here in place of flint which is rare and of mediocre quality), e.g. in the Lihult type of Bohuslän, along the west coast of Norway and around the large lakes Vänern, Vättern and Mälaren; this Nöstvet type,[809] named from Nöstvet south of Oslo, has axes of fine-textured greenstone which show an evolution in cross-section from triangular through trapezohedral to rhombic and were either derived from kitchen-midden peoples[810] or evolved on parallel lines with these[811]—it was probably contemporaneous with the Komsa-Fosna culture.[812] The vases, both in form and decoration, go back directly to Ertebölle models; kitchen-middens also occur along the east coast of Sweden (Gotland to Finland and the Åland Islands) where the culture possesses elements from Mullerup and megalithic cultures.

Kitchen-middens, now sunk beneath the sea, are found in south Denmark, at Rügen and in Kiel Bay.[813] They also occur at Hastings and Lower Halstow in south England,[814] in Scotland[815] (e.g. Firth of Forth, Moray Firth, Outer Hebrides), all round the Irish coasts[816] and to the Tagus[817] where they belong to outposts of the epipalaeolithic survivors of the Capsians, or late Natufians of Palestine, and coastal Asturias and Catalonia.[818] The *Skrivespalter* has been traced from Scandinavia over the North Sea coast into Belgium, France and Italy,[819] and flint implements, similar to those of the kitchen-middens, into the French Campignian and Lower Rhine[820] and even into central Europe.[821] The dense kitchen-midden settlements of the southern shore of the North Sea and the Baltic are still submerged.

The kitchen-middens were coeval with the Campignian of west Europe,[822] and they extended over 2000 years of the Atlantic period.[823] This is borne out by their pollen-floristic relationship (their charcoal contains oak in great preponderance with birch, elm, aspen, hazel, alder, willow and ash[824]) and by their relation to the Tapes-Littorina Sea. They were distributed along the shore of that sea,[825] often termed the *Stenålderhafvet*[826] ("stone-age sea") or *Neolithhafvet*.[827] Although often regarded as belonging to the maximum of this transgression,[828] there is reason to believe that they preceded it[829] (the Lihult axes in Bohuslän were pre-Atlantic[830] and the Nöstvet culture was contemporaneous with the oldest Ostrea banks[831]) and the middens pass beneath sea-level in south Jutland and Schleswig-Holstein to reappear on the Belgian coast and at Hastings. The culture survived in Scandinavia from the Old Stone Age up to the close of the New Stone Age.[832]

The middens continue into neolithic time as proved by vases and celts at Langeland, by the bones of domestic animals (ox, pig, sheep, goat), and by grains of wheat in the upper shell-mounds at Limhamn in south Sweden. Many German and Swedish archaeologists, including G. Kossina,[833] believe

therefore that the neolithic civilisation arose spontaneously in Scandinavia. The cultural backwardness of this peninsula, however, which is shown in the late arrival of the copper and iron ages, suggests with other facts that the neolithic peoples were invaders from the south-east.[834]

The Asturians,[835] who dwelt in caves on the Spanish coast of the Bay of Biscay and lived on shell-fish, were a remnant of the Magdalenian[836] who survived to be contemporaries of the kitchen-midden peoples farther north.

Domestic animals. The origin of the domestic animals is still uncertain and much disputed.[837] Much of our evidence comes from the Swiss lake-dwellings[838] where the importance of the domestic animals increases with decreasing age from the earliest time,[839] where *Cervus elephas* was predominant (Ger. *Hirschzeit*) and where the primitive domestic animals were *Canis familiaris palustris*, *Sus scrofa palustris*, *Capra hircus palustris*, *Ovis aries palustris* and *Bos taurus brachyceros*, all forms recognised by Rütimeyer. The dog was apparently the first animal to be domesticated (see p. 855). T. Studer[840] recognised seven races, now usually reduced to five,[841] based on the absolute size and the relative development of the length and breadth proportions of the cranium. A. Brinkmann,[842] with the concurrence of many writers, distinguished two main races of diphyletic origin, though it seems probable that the oldest domestic dogs were descended from an ancestral species of wolf allied to or identical with the dingo.[843] Dog is known from the Maglemose stations[844] of Mullerup, Holmegaard and Svaerdborg, from the Ertebölle kitchen-middens,[845] from Morbihan,[846] from Viste near Stavanger[847] and from the Swiss lake-dwellings[848] (= *Canis familiaris palustris*). The neolithic and Bronze Age sheep was a small "goat-horned" variety which is known from representations of the third millennium B.C. in Babylon and may have been domesticated in Turkestan about 6000 B.C. but its origin is uncertain since wild prototypes are unknown.[849] The neolithic goat, descended possibly from Pleistocene goats,[850] belongs to a species which still lives in Crete and is widely distributed in western Asia. The domestic pig is derived from the wild boar which is native to North Africa, western Asia and Europe (*Sus scrofa ferus*) and was domesticated independently in various parts of Europe, e.g. Sweden, north Germany and in Switzerland where pig occurred in the Swiss lake-dwellings[851] (*Sus scrofa palustris*).

The two main groups of the domestic ox, the long-horned, broad-browed variety and the short-horned, narrow-headed variety (*Bos taurus longifrons*) are both found in the Danish and Swiss Neolithic. They were derived from *B. primigenius*.[852] Churns for the making of butter are known from the Swiss lake-dwellings.[853] The domesticated horse reached Denmark during the megalithic period, probably from the grasslands of south Russia where the domestication may have taken place.

Later peoples. The food-gathering mesolithic peoples were succeeded by neolithic invaders whose civilisation, based on agriculture (wheat and barley) and the domestication of certain animals, first arose in western Asia and Egypt somewhere about the fifth or sixth millennium B.C. An account of these important movements and cultures, which lies more properly in the domain of archaeology than of geology, is outside the scope of this work. The full and excellent treatises now available[854] show that while Europe was still sunk in epipalaeolithic barbarism, true civilisation, such as that of the

Sumerians, had arisen and was firmly established in the Ancient East. The migration period of the neolithic culture across Europe from east to west may have been 6000 years, for copper about 2500 years, and for bronze about 2000 years.[855]

The megalithic civilisation of the stone graves (dolmens, passage graves and stone cists, developed in this order) had no forerunners in the older cultures of the north. These Bronze Age invaders or "Beaker men"[856] (= Round Barrow men) were stock raisers and practised agriculture (barley, wheat, flax). They had polished axes, perforated axe-hammers and arrow heads and made ornamental pottery. West Europe (Iberian Peninsula, France, British Isles and south Scandinavia) was their home—they arrived in Great Britain in Bronze Age I or *c.* 1900 B.C. The polished stone "celt", type fossil of the Neolithic, apparently dates back to Boreal time in Kunda and to the end of the Pleistocene in the Ukraine.[857]

The settlements of these broad-headed peoples were chiefly on loess, e.g. north Bohemia, Moravia and Thuringia, or on sandy patches, e.g. Oder mouth or shores of the Zuider Zee.

While plants, including fruits, were collected and used by early man,[858] cereals and other cultivated plants were of later introduction[859]; the occurrence of wheat, claimed for various mesolithic localities,[860] is seemingly doubtful.[861] The ultimate source of wheat (wild emmer) and barley is the Near East.[862] The megalithic people of Denmark cultivated little else but wheat. The battle-axe or single-grave people grew exclusively barley (p. 1497). Emmer and barley are associated with Bronze Age barrows in England.[863] Oats first appear in central Europe and Denmark during the Bronze Age and occurred with rye in England during the Early Iron Age.[864] Flax-seed is known in central Europe from late-neolithic time. Further light on the history of cultivated plants is thrown by researches in the lake-dwellings.[865]

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CHAPTER XXXVI

PLEISTOCENE STRATIGRAPHY: GENERAL CONSIDERATIONS

The classification of the Quaternary has been attempted in various ways: by reference to the succession of glacial events, to vertebrate faunas, to the evolution of human industries, and to the invertebrate faunas in marine terraces. But the subdivision and classification of the Quaternary Era form a very tangled skein. Normal stratigraphical methods, applicable to older formations, break down to some extent when applied to the Quaternary. The marine formations are generally exposed only on the continental margins and its terrestrial deposits have few fossils and are thin, varied and interrupted and often juxtaposed instead of superposed. Lithology is controlled by the underlying bedrock and continuity cannot be assumed without continuous exposures which are unusually liable, being unconsolidated, to soil movement of various kinds. Successions, therefore, are apt to be local and limited: altitudes are of unproved worth. The period was very short and too short for any appreciable evolution of invertebrate or vertebrate life—the Pleistocene genera had already appeared in the Pliocene; and palaeoliths have not the certainty of continuously evolving organisms and are absent from the earlier horizons. Moreover, while the organisms were liable to slight evolu tionary change, they were subject to great migrations by the ice-sheets and the attendant physical and climatic events which caused a replacement of Pliocene survivals by "modern" forms and a mixing of faunal elements that reached a maximum during the last glaciation.

Nevertheless, the Glacial period, thought by early geologists to have been one and indivisible, has been shown by later studies to have been complex in its events. Mild or genial epochs between the glaciations have been established.* During these interglacial times the ice receded or, in the extreme cases, disappeared completely in response to pronounced or widespread climatic changes, distinct from the small and strictly localised variations that brought about transitory oscillations of the ice-margin. With these epochs, to unravel which much patient research is still necessary, the age and distribution of the present and past faunas and floras and the appearance of man in the Old World are intimately connected. Agreement has still to be reached on the number of the glacial epochs and upon the relationship of these to human cultures.

Historical. Repeated glaciation was suspected by L. Agassiz for the insufficient reason that erratics occurred beyond the outermost moraines. Collomb,[3] in the Vosges, was the first to recognise a double glaciation though

* While the English-American "Ice Age" or "Glacial period" comprises all the Pleistocene glaciations, the French *période glaciare* and Scandinavian *istid* mean both this and a single glacial epoch. The German *Eiszeit* signifies one glacial epoch, the whole Ice Age being termed *Eiszeitalter*. Glacial period is used throughout this book for the whole Pleistocene and epoch for the separate glacial divisions in accord with the recommendations of the International Geological Congress.[1] It has, however, been suggested [2] that the major units be called "ages" and the corresponding deposits "stages".

I. Venetz[4] had earlier (1833) conjectured it for the Alps from the existence of two morainic zones and the lignites between tills (A. Escher[5] also noted these at Dürnten) and because glacial erosion was difficult to reconcile with glacial deposition. A. C. Ramsay[6] and R. Chambers[7] found evidence of a twofold glaciation in Great Britain.

A. Morlot's observations in the valley of the Dranse[8] led him in 1855 to similar conclusions. Partly palaeontological and partly based upon the contrast presented by the compact lower till and the oxidised and more friable upper boulder-clay and by the inner and outer moraines, his deductions anticipated by many years those of Penck and Brückner[9] and other glacialists. O. Heer,[10] introducing the word "interglacial", showed somewhat later (1864) that the double glaciation postulated by Morlot was true for the whole of Switzerland since the mild interbedded flora was incompatible with extensive glaciation. The *Schieferkohlen*[11] or compressed vegetable layers contained in addition to pine, spruce, fir, larch, yew and birch, *Quercus robur*, *Acer pseudoplatanus*, *A. platanoides*, *Tilia platyphyllos*, *T. cordata*, *Fraxinus excelsior*, *Hedera ledrix*, *Ilex aquifolium* and *Buxus sempervirens*.

Although S. Gras[12] supported this view for the Dauphiné Alps and Rhône valley, partly because loess occurred between the boulder-clays, and F. Mühlberg[13] did the same because the schotter had a similar mode of occurrence, many geologists including A. Favre, P. Lory, A. Falsan, G. de Mortillet, B. Gastaldi and C. Grad continued to interpret the evidence as implying only oscillations. This was disproved by the discovery of the Hötting Breccia between two moraines (see p. 936), of a similar relationship at Pianico, and of the multiple fluvioglacial series by Du Pasquier[14] and others.

The Swiss conclusions, championed in France by M. Boule,[15] found favour in Britain, particularly by J. Croll[16] and J. Geikie,[17] the one appealing to astronomical causes of a recurrent nature, the other invoking these and certain Scottish evidence that his brother emphasised[18] and affirming a fourfold glaciation for east England. The British interglacial epochs were primarily based upon sands and gravels sandwiched between tills, the so-called Middle Glacial Sands and Gravels of England (see p. 991) and Scotland,[19] and later upon the shelly drifts (see p. 630). O. Torell's recognition in 1865 of a Younger Baltic Ice-stream was the point of departure for the interglacial theory in north Germany. This was borne out by the double system of striae[20] in Scania (associated with drifts of different erratic content[21]), Bornholm, Gotland and north Germany, and the two distinct German drifts, recognised by G. Berendt[22] and K. A. Lossen[23] and interpreted as products of separate glaciations by Helland in 1879 (see p. 939) after the glacio-natant hypothesis had been abandoned.

In Russia,[24] the first evidence of an interglacial flora was discovered in 1890 near Moscow by N. I. Krischtofowitch but was received doubtfully until N. N. Bogoljubow found plant remains near Likhvin in 1904.

In North America, where the simple monoglacial succession was given as Glacial, Champlain (or Terrace) and Recent, the evidence was twofold. The buried soils (with shells and bones) discovered about 1870[25] in the Middle West (Illinois, Ohio and Minnesota)—the best Pleistocene succession in the world (see p. 967)—were first regarded as tokens of deglaciation by J. S. Newberry,[26] an opinion afterwards adopted by W. J. McGee[27] for Iowa and generally by Chamberlin.[28] The second class of evidence was physiographic: the topography and state of weathering of the main mass of drift

contrasted with the Extramorainic Drift[29] or Fringe[30] or "Attenuated Border".[31] This outer zone has few erratics or striae and no bounding terminal moraine. Chamberlin[32] showed it was the product of an older glaciation in Pennsylvania and Salisbury[33] did the same for New Jersey.

Interglacial epochs, whose climate and duration are not elucidated by polar studies, can only be established by a concerted attack along many lines, namely, by combining results gained from topographical, lithological, stratigraphical and palaeontological investigations and from human cultural sequences, based upon man-made implements and on stages in his skeletal evolution.

Topographical proof. One of the strongest proofs was early seen to be the topographical contrast between the "outer" and "inner" drifts (S. V. Wood's "major" and "minor" glaciations[34]). The outer drift, styled the fringe or attenuated border in North America (see above) and Lower Diluvium in north Germany, was noticed by A. Guyot[35] in Switzerland, by H. Bach (1869) in Württemberg, by T. Taramelli (1881) in Italy, and in England[36] by R. H. Tiddeman, J. Geikie and S. V. Wood. Except in rare cases,[37] it has the impress of great antiquity. It frequently occurs in detached patches, as in depressions and sheltered localities which owe their isolation to discontinuous deposition or to later destruction of a once-continuous sheet.[38] Its surface is mature and often featureless, except where it has been submaturely dissected as in the Dissected Till Plains west of the Mississippi and those of the Kansan glaciation where the larger streams are incised to depths of 200–400 ft (60–120 m) and tributaries to at least 200 ft (60 m). Its epigenetic valleys are much wider than those in the newer drift (the ratio is in places 10:1[39]), hollows are partially or wholly filled up, lakes are few, and streams have shortened and graded courses. Tributaries have branched out in dendritic pattern[40]; overflow valleys, as in the south-east Pennines,[41] have suffered much from subsequent subaerial attack; the subglacial *Rinnenseen* have been filled in[42]—the Lüneburg Kieselgur lies in several such lakes; the occasional osar present softened outlines,[43] as in Holland; drumlins, as in the Chalky-Jurassic Boulder-clay of East Anglia,[44] have been largely obliterated; and moraines and kames, though sometimes present,[45] as on the Saale (or even the Elster glaciation of north Germany or on the Kansan and Illinoian drifts of North America, may be recognisable less by their form than by their structure and composition.[46] Osar, remarkably fresh and belonging to the Saale glaciation, are still preserved in Silesia and north of Bremen[47]—the coarse gravels allowed the rain waters to percolate (cf. p. 505).

The drift is deeply and intensely weathered: its upper layers are iron-stained and leached; its boulders, unless for example in hard quartzite drift,[48] are in an advanced state of decay, being either quite disintegrated or having a deeply weathered rind. Felspars are kaolinised and the lime has been removed so that siliceous, argillaceous and ferruginous materials predominate. The rock, e.g. the Austrian *Nagelfluh*, is sometimes so hard that it may be used as a building stone.[49]

The border thins to a feather edge which is difficult to fix with exactness. Beyond it lie scattered erratics and occasional trains of gravel,[50] though the rarity of these may be original,[51] and, as in the Mississippi region, may be due to the clayey nature of the primary material as well as to the later destruction; for in the east, where there is a dearth of clay, outwash does occur, e.g. in the Illinoian outwash in the Allegheny and Susquehanna rivers. Terminal

moraines are rare but have been noted in Holland[52] where they run southwards from the Zuider Zee over Amersfoort (= Amersfoort Stage), and between Nijmegen and Hülserberg via Kleve and Krefeld rise as a steep ridge 50 m above the surrounding plain (see p. 1167). They have been seen elsewhere in Europe[53] (Germany, Galicia, Russia, Switzerland and England) and in North America[54] (Iowa, Illinois, Wisconsin).

The Newer Drifts, as emphasised repeatedly for the circumbaltic lands,[55] differ strikingly from this Older Drift in their relief and physical characters: the difference has been presented graphically.[56] The surface is fresh and little subdued by meteoric modifications—the average depth of leaching of the Wisconsin drift is perhaps 2·5 ft (76 cm).[57] The topography is restless and confused, abounding in moraines and lakes and steep slopes. The drainage is immature, as is illustrated by maps of Europe's peat distribution,[58] and does not fall continuously except along the bigger streams. The materials are only slightly altered, even porous sands being calcareous almost to the surface and richer in plant foods than those of the older drifts. The bounding moraines, as in Switzerland and North America, are more lobar.[59] Notable differences between soil profiles have been used for accurate mapping of the drift-borders, e.g. the Wisconsin and Illinoian boundary in Indiana.[60] The Dutch drifts, which belong to the earlier glaciations (see p. 941), differ from those of the last glaciation in north Germany.[61]

In the mountains where depositional records give place to signs of erosion, and where evidence of interglacial recessions has been mutilated or destroyed, different "erratic heights" (see p. 40), changes in the direction of glaciers, as in the Sierra Nevadas,[62] and stream gorges (enclosing drifts reposing on glaciated surfaces in the sides of U-valleys) may, as in the Finger Lakes region of New York, provide the required sequence.[63] Multiple benches have been regarded as cyclical (see p. 320); double U-shaped elements suggest a double glaciation for Greenland.[64]

Stratigraphical. Interglacial or "warm" epochs are proved stratigraphically by sheets of till, fluvioglacial deposits or loess which are separated by zones of weathering and by fossiliferous beds, either fluviatile, lacustrine or marine, e.g. on Long Island, or by peat, forest or other vegetation layers, lignites, soils, tufas, iron-ores and diatomaceous earths[65] (e.g. Jutland and the Lüneburger Heide). Deceptive relations may spring from landslips, creep or human disturbance of the ground.[66] The epochs may be indicated too by erosive discordances, as in Iceland[67] where they are associated with lake-clays, fluviatile and aeolian accumulations, etc. (collectively designated palagonitic tuff) or by weathered sheets of drift, buried with their glacial epigenetic and stream-eroded valleys,[68] sometimes hundreds of feet deep,[69] e.g. in the Rocky Mountains of Montana and the San Juan Mountains of Colorado (in the latter case exposing rocks which first appear in later tills). The upper boulder-clay may clothe their sides and floors and if thin may be unable to disguise them or impose its own configuration. The drainage on the earlier surface may have differed from the present. This is shown by local variations in the depths of the drifts, in the widths of the valleys, and in the angles at which the tributaries join the trunk stream.

The buried drift is frequently weathered and decayed to a great depth, especially in the *geologische Orgeln*—in Germany it may amount to 27 m.[70] The alteration was by solution, hydrolysis, the formation of colloids and crystalloids, the action of sun and frost before plants advanced upon the

ground and of organic acids after the vegetable carpet was established. The order of the change is from oxidation (especially of iron compounds), the pioneer reaction, through leaching of the primary carbonates, to complete decomposition of the drift, including its "clay minerals" which form the sticky gumbotil.

These weathered, brown or yellow layers, the North American "gumbotils"[71] (in which decomposed stones are still visible by faint outlines), are especially thick in northern Italy (*ferreto*, a sticky, impermeable red clay up to 75 m thick) and Austria (*Nagelfluh*), and are important in north Germany[72] where a single profile may intercept two weathered zones. Weathered striae and pedestal boulders accompany them.[73] The depth of the decomposition depended on many variable factors, such as climate, topography, drainage, permeability and chemical composition of the drift. Permeable drifts in which decomposition was very deep may have their age determined by the extent to which decomposition has penetrated the contained boulders.[74] The gumbotils of North America, because of their distinctive characters, wide distribution and topographical positions, are the most satisfactory criteria for distinguishing the older drifts (see p. 967). They reflect different types of drainage: in flat uplands with poor drainage typical gumbotil is found, while open-textured *silttil* occurs in well-drained areas and *mesotil* in areas of intermediate conditions of drainage.[75]

Oscillations of interglacial magnitude may also (but not necessarily) be indicated by the following; the orientation of boulders in the drifts—in north Germany, those of the Elster glaciation are orientated east–west, of the Saale north–south (see p. 940); persistent beds of sand and gravel of wide extent[76] (see above); interbedded casts of ice-wedges, block fields, involutions and other solifluxion features; discordant trends of morainic groups or of current bedding in outwash sheets[77]; superimposed tills of different composition, colour, texture or structure,[78] e.g. the Nebraskan and Kansan drifts in Iowa, the drifts of Illinois and the Dutch drifts; different erratic ratios, stone-counts and quotients[79]—in north Germany, each drift has its distinctive stone-count, the Elster glaciation being distinguished over part of its course by 60% of erratic boulders from Finland and Åland, the Saale by 60% from Norway and west and south Sweden, the Warthe by 40% from Finland and Åland, and the Weichsel by equal distributions (see p. 939); the composition of mechanical fractions (by sieves) 0·5–1·0 mm, 1–2 mm and 2–20 mm[80] (limestone, dolomite, quartz sandstone, felspar, etc.) in Latvia; different grain sizes[81]; heavy mineral contents[82]—in Holland[83] the Reuverian has tourmaline, zircon, rutile (with stauralite, disthene, andalusite, and sillimanite) and the Tegelen has garnet, epidote and amphibole; landslips along the sides of valleys, as in the Alps[84]; striated pavements[85]; faceted pebbles meeting at an angle, the one set fresh, the other set weathered[86]; striae preserved on the lee-sides of earlier ice-worn facets[87]; the microflora of the till[88]; intervals of soil-formation in coastal dunes of Australia (Victoria[89]); variations in the productivity of the major phosphatic islands of the west Pacific[90]; and the contents and sediments of caves[91] (apart from their organic remains), e.g. in the Mediterranean and central European areas—loose, unstratified cave-earths indicate wind-action (arid climate), breccias, frost, stalagmites moist conditions, and marine deposits (with a warm fauna) warm conditions.

Cross-striae may suggest an interval of deglaciation. Two or more sets of striae are observed crossing obliquely or transversely without intermediate

bearings on a single face or lie on adjacent faces which may meet along a bevelled edge.[92] They were first observed by A. Escher[93] in Switzerland and by E. Collomb[94] beneath the Rosenlaui Glacier and are usually confined to low ground where the ice oscillated and erratics from various directions mingled. They have been accepted as proof of a two-fold glaciation (Charpentier[95] early ascribed the Swiss ones to an ice-sheet and local glaciers), notably, as in the Baltic region and north Germany (see above), where they run regularly over wide territories. This is the more probable if they are associated, as in Wisconsin,[96] with different boulder-trains at different horizons in the drift, or, as in Finland,[97] with grooves in the drift plains. The earlier set may have been protected by thick drift,[98] especially if the surface had hollows, or may have been preserved because the later ice was thin and feebly erosive.[99]

Such cross-striations, as affirmed for the Baltic, attended oscillations of less than interglacial size[100] and accompanied changes in the boundary and slope of the ice, having been directed perpendicularly to the edge in "axi-radiant" fashion,[101] as has been seen for instance in connexion with the modern Richter Glacier of Argentina.[102] They also arose from the varying strengths of opposing ice-centres, as when these migrated (see p. 670), or from changes within a single current of ice incidental to vicissitudes during the declining phases[103] and thinning of the ice and the growing influence of the relief upon its shrunken outlines and flow.[104] They may have sprung too from variations in the resistance to flow, due to the removal of features by ice-erosion,[105] or in the direction of flow consequent upon faulting,[106] a warping and tilting of the land[107] or obstructive roches moutonnées.[108]

Proof in mountains outside the ice-centres may also be physiographic. It may be furnished by the progress in the decay of glacial boulders and drifts and in the elimination of lakes as a result of the lowering of outlets or of deltaic advances; by the depth of stream-cut valleys in moraines and drifts; and by the size of stream terraces carved in valley-trains. Periglacial river-terraces are also of service but in the present state of our knowledge have only a limited value.[109] Changes in sea-level, regional uplift and local tectonic movements combine to complicate the climatic record (see p. 1026).

Polyglacialism in lower latitudes is suggested by geological data of quite a different kind. Such are the ancient coastal dunes which eustatic lowerings of the sea made possible (see p. 1358) and the repeated weathered zones in the tropics, e.g. at Mombasa, which with the evidence of repeated higher ocean levels denote interglacial epochs in Greenland and Antarctica.[110]

Rapid or abrupt changes in lithology, both vertically and laterally, together with the unconsolidated nature of the deposits which favours slumping and quickly obscures exposures, make it difficult to infer the conditions between sections and even more hazardous to correlate over long distances. For this reason palaeontological aid is particularly welcome.

Palaeontological. The Pleistocene had in the main two contrasting floras and faunas, as is shown for example by the British non-marine mollusca.[111] The warm assemblage included *Corbicula fluminalis*, *Paludina diluviana* and other molluscs among the invertebrates[112] and the *faune chaude* (see p. 791) among the vertebrates—the warm trio of *Hippopotamus amphibius, Elephas antiquus and Diceros leptorhinus* is as truly interglacial as is the cold trio of mammoth, woolly rhinoceros and reindeer truly glacial. Within the glaciated country, they are preserved between successive drifts

and outside it between loess and outwash sheets or in river-terraces and caves. Hippopotamus could have lived in west Europe only in an oceanic climate with mild, open winters. Like its living representative, it was adapted to a warm aquatic life.

Corbicula fluminalis, which appeared in the upper Pliocene,[113] e.g. in France, Italy, Greece, Hungary and England (Norwich Crag; cf. p. 599), is now found[114] throughout Africa from Natal to Egypt, and in Asia from Palestine through Transcaucasia, Turkistan and central Asia to Japan. During the Pleistocene it had a wider distribution; it spread farther north in Europe; it occurred in England[115] (the species is strictly *C. consobrina*[116]), e.g. in Somerset (related to the raised beach at Weston-super-Mare) and in deposits of the ancient Thames-Rhine system, e.g. at Sutton and Copford in Essex, in the Thames terraces, as at Oxford, Crayford, Ilford, Grays and Clacton, in the Cam at Barnwell, in the interglacial gravels of Kelsey Hill and March (= derivative) and on the bottom of the North Sea. It also occurred in Belgium[117] (Campignien and Moséen), Holland,[118] north Germany[119] (e.g. Halle, Thuringia, Fläming), France[120] (e.g. Abbeville), Hungary[121] and parts of Russia[122] and Siberia.[123] The Nile is to-day 10°C warmer than the European rivers.

As a rule, however, non-marine mollusca do not aid much in establishing a succession, except by their very presence: their biotic requirements are, generally speaking, relatively unrestricted, they are liable to be locally conditioned, and they are readily removed.

Within the glaciated territory, interglacial horizons are rarely more than fragmentary. Later glaciations have removed them and the older glacial signs by direct glacial scour or by fluviatile or fluvioglacial action, as rolled bones and clay pebbles in the deposits testify.[124] Earlier horizons especially have been subject to greater chances of destruction or, if they survive, have been buried deeper. Since earth-movements have not brought the lower accumulations to the light of day, interglacial horizons can only be reconstructed by combining profiles in coastal sections, as in Britain, Denmark and north Germany, and by sections in incised meanders, as in the Niemen basin,[125] or from information supplied by bore-holes sunk for economic purposes. They are obviously best studied if the drifts are spread out over vast plains, as in north Europe and North America, and are much less satisfactory in the restricted field of the Alps or other mountain centres of ice-radiation where the relief was higher and the flow more vigorous.

In deciphering the succession, species such as land mammals which can easily migrate are least suitable and carnivores are less trustworthy than herbivores which rely directly upon vegetation. Eurythermal forms, i.e. those such as mammals or warm-blooded animals which can bear considerable changes of temperature and have wide variability and powers of adaptation, are less useful. Small mammals withstand worsened conditions better than bigger ones which, if they wander less frequently, find the necessary space for their continued existence free from competitors already adapted to the environment. Yet the smaller creatures show the greatest amount of extinction and probably of speciation. Insects, whose development periods depend upon the summer temperatures, are also important. Much can be done where collections of fossil mammals are very rich, as in the Great Plains of North America where, for example, the bison's relations to the glaciations are as follows[126]: *Bison latifrons* and *B. alleni*, Yarmouth;

B. antiquus barbouri, Sangamon; *B. antiquus*, Mid-Wisconsin; and *B. bison*, Recent.

The great adaptive powers of animals[127] and the mingling of neighbouring biotopes to-day show the need of caution in the use of this class of evidence, which is perhaps less reliable than soils or other physical evidence which are not subject to such adaptations. Thus the lion lives in open zoological gardens in Hamburg and London in frosty winters and in parts of Abyssinia where the winter temperature scarcely exceeds 0°C and in the coniferous forests of Mount Elgon,[128] and the woolly coated tiger crosses frozen rivers to feed on the reindeer in Manchuria.[129] The musk ox, an exclusive denizen of the tundra to-day, lived on the Pleistocene steppes also and the reindeer is adapted both to tundra and boreal forest.

The European Pleistocene distributions may have been as follows[130]:

(1) Tundra: *Vulpes lagopus*, *Gulo gulo*, *Lepus timidus*, *Dicrostonyx* and other lemmings, *Tichorhinus antiquitatis*, *Rangifer tarandus* (tundra form), *Ovibos moschatus*, *Elephas primigenius*.

(2) Subarctic coniferous forest: *Ursus arctos*, *Gulo gulo*, *Lynx lynx*, *Cervus elephas*, *Alce alces*, *Rangifer tarandus* (forest form), *Bos primigenius*.

(3) Temperate deciduous forest: *Ursus arctos*, *Lynx lynx*, *Dicerorhinus merckii*, *Cervus elephas*, *Alce alces*, *Bos primigenius*, *Elephas antiquus*, *Trogontherium* and *Castor*.

(4) Warm, continental steppe: *Ochotona*, *Allactaga jaculus*, *Marmota bobak*, *Equus przewalskji*, *E. hemionus*, *Saiga tatarica*.

(5) Loess steppe: fauna as in (4) with *Vulpes lagopus*, *Lepus timidus*, *Tichorhinus antiquitatis*, *Rangifer tarandus*, *Bison* cf. *priscus*, *Ovibos moschatus*, *Elephas primigenius*.

Ursus spelaeus, *Felis spelaea* and *Crocuta spelaea* had no biotope preference.

W. Soergel[131] calculated that 89·5% of the interglacial fauna were forest forms and 83% of the glacial fauna were forms of open landscape.

Plants, which are better preserved than Tertiary plants and occur in fossiliferous layers and in tufas, e.g. at Celles-sous-Moret near Paris and at Cannstadt and Taubach in Germany,[132] have been widely employed in establishing interglacial epochs: they include, for example, about 20 hepatics and more than 250 species of mosses.[133] Nevertheless, they represent a mere fraction of those that were then living. Thus only about 250 species of Pleistocene plants have been identified in all North America though probably more than 90% of the plants now living in the region were then in existence.[134] Though dependent upon food, shelter and not too excessive competition, as well as upon climatic factors, plants are sedentary and enable us to apply more rigorous methods and to determine maximum, minimum and mean temperatures and humidities, the duration of the vegetative period, etc. *Taxus baccata*, *Trapa natans*, *Vitis vinifera*, *Brasenia purpurea* and *Dulichium spathaceum* are among the plants[135] that denote warmer conditions. Other widely distributed plants include *Alnus glutinosa*, *Ilex aquifolium*, *Carpinus betulus*, *Corylus avellana*, *Picea excelsa*, *Tilia platyphyllos*, *Ceratophyllum demersum*, *Lycopus europaeus*, *Menyanthes trifoliata*, *Nuphar*, *Nymphaea* and *Potamogeton*.[136] The well-known tufas of Weimar[137] contained beech, poplar, *Tilia ulmifolia*, *Corylus avellana*, *Quercus robur*, *Juglans regia* and *Lonicera*. *Naias flexilis* (fig. 171) has been found in Poland in the Sando-

mirian and in Masovian I and II and *Naias marina* in the last two horizons[138] and in several other European localities.[139] *Fagus sylvatica* lived in the Mindel-Riss and Riss-Würm interglacials in both north and south Germany.[140] In Russia,[141] plants grew north of their present range and north of 60° N. Lat., e.g. *Acer tataricum, Tilia platyphyllos, Aldrovanda vesiculosa, Salvinia natans*, red beech and white beech. During the great interglacial warm plants extended to the White Sea some 400 miles (*c.* 650 km) north of their present range; deciduous forests formed a broad belt across Russia from the north-east to the south-west; and wooded steppe spread to the Black Sea.

Pollen analyses of various European interglacial deposits,[142] which have been increasingly made in recent years, show not only the wider distribution of certain trees, e.g. *Rhododendron ponticum* and *Buxus sempervirens* in the

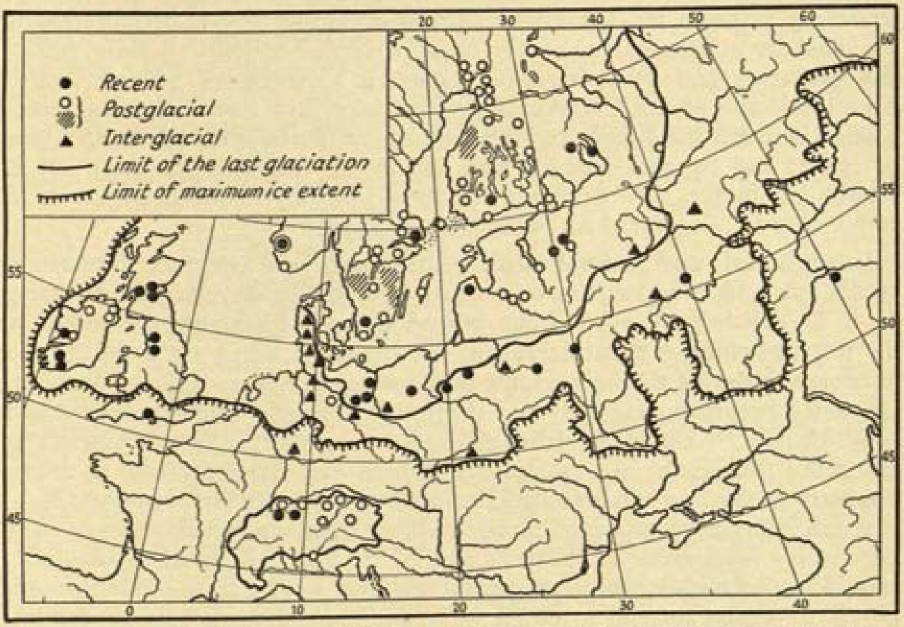

FIG. 171.—Localities in Europe of *Naias flexilis* in interglacial, postglacial and recent times. A. L. Backman, *Acta Bot. Fenn.* 43, 1948, p. 6, fig. 1.

Alps, fir as far north as north Germany and central Russia and *Ilex aquifolium* in Mark Brandenburg, but a complete floral succession from arctic to warm and back again (see below). The interglacial flora at Phoeben and other north German localities implies an oceanic climate with mild winters.[143]

Certain European colonies of freshwater species, e.g. *Diaptomus zacheriasi* and *Asplanchna syrinx*, have been regarded as relics of an interglacial epoch.[144] Interglacial deposits which were laid down in freshwater lakes, e.g. in the Lüneburger Heide (13 m thick), contain diatoms which embrace hundreds of species: important genera are *Cymbella, Stauroneis, Navicula, Gomphomena, Eunotia, Synedra, Fragilaria, Surirella, Nitzshia, Melosira* and *Stephanodiscus*.[145]

The existence of a steppe period in interglacial time is uncertain. Such a period has been thought to have occurred between two forest phases (see

p. 910) or to have either ended[146] or to have initiated and ended[147] an interglacial epoch.

In North America, manatee has been found fossil in New Jersey, tapir and peccary in Pennsylvania, panther and ground sloth in central Alaska, and marmot in New Mexico at an altitude of 5900 ft (1800 m) or 4000 ft (1220 m) above its present limit. Multiglaciation is also hinted at by the present ranges and hybridisation of certain species in the eastern United States[148] and by certain Alpine relics (see p. 1391). Many present warm species may be interglacial[149]—they are more difficult to recognise than cold species.

Miscellaneous methods. The evidence may be supplemented by considerations concerning palaeolithic cultural stages (see pp. 841, 1028), by eustatic changes of sea-level (see p. 1261), by tectonic movements, as elaborated for north Germany (see p. 1265), including the supposed interglacial faulting in the Baltic region (see p. 364), and the interglacial uplift and trenching affirmed for the lower Mississippi valley.[150] Corroboration is provided by marine faunas of the coast of New England[151]—these reflect less glaciation and a less vigorous Labrador Current—of western North America[152] and of the Old World (see pp. 944, 959, 1007); by the interchange between the Pacific and Atlantic deeper living boreal faunas[153] (see p. 1089); and by core-samples from the ocean floor (see p. 921). It is sought too in the climatic curve resulting from astronomical causes held responsible for the glacial succession (see p. 1545).

Interglacial and interstadial. The distinction between interstadial oscillations and interglacial recessions, though vital, is more or less arbitrary. As R. D. Salisbury[154] pointed out, it depends upon the nature and extent of the physical changes that intervened, and upon the values we assign to the temperature during the interval, the duration of the retreat, and the distance, calculated both proportionally and absolutely, through which the ice retired —W. Upham,[155] a monoglacialist, estimated one retreat in North America at 500 miles (800 km). An interglacial climate may have obtained in south Germany at a time when interstadial conditions persisted farther north.[156]

A full interglacial sequence, unlike an interstadial one which registers only a transition from arctic to subarctic and boreal, and back again to subarctic, should have a middle temperate period and give a cycle from arctic through boreal to temperate and a return to arctic,[157] i.e. from a treeless tundra, through birch forest and conifer forest, to the mixed deciduous forest of the climatic optimum, and thence back through a coniferous forest stage to treeless tundra again. The figure (fig. 172a) shows the following phases:

VI. Pine, fir, birch
V. Spruce, fir
IV. Hornbeam
III. Mixed oak forest
II. Alder, pine, mixed oak forest with hazel maximum
I. Birch, pine.

The pollen diagram of this Eemian or last interglacial may be compared with that from the Saale-Warthe interval (fig. 172b) and with that from the Elster-Saale interglacial (fig. 172c; see p. 909).

Successions of this kind are rare in any one profile though instances have been recorded,[158] e.g. from Stade (Hanover), Phoeben and Rixdorf, Quaken-

brück (55 m thick), east Mark Brandenburg, Thuringia, south Jutland, Poland and Latvia. As generalised for Jutland and north Germany,[159] it shows that the interglacial floras immigrated in the same order as post-glacially (see p. 1438), viz. (*a*) Dryas flora of dwarf birch, arctic willow, etc., with mosses (*Hypnum turgescens*, *H. giganteus*) and water-plants, e.g. *Potamogeton filiformis*; (*b*) *Pinus sylvestris*, *Populus tremula* and *Betula alba*; (*c*) *Picea*

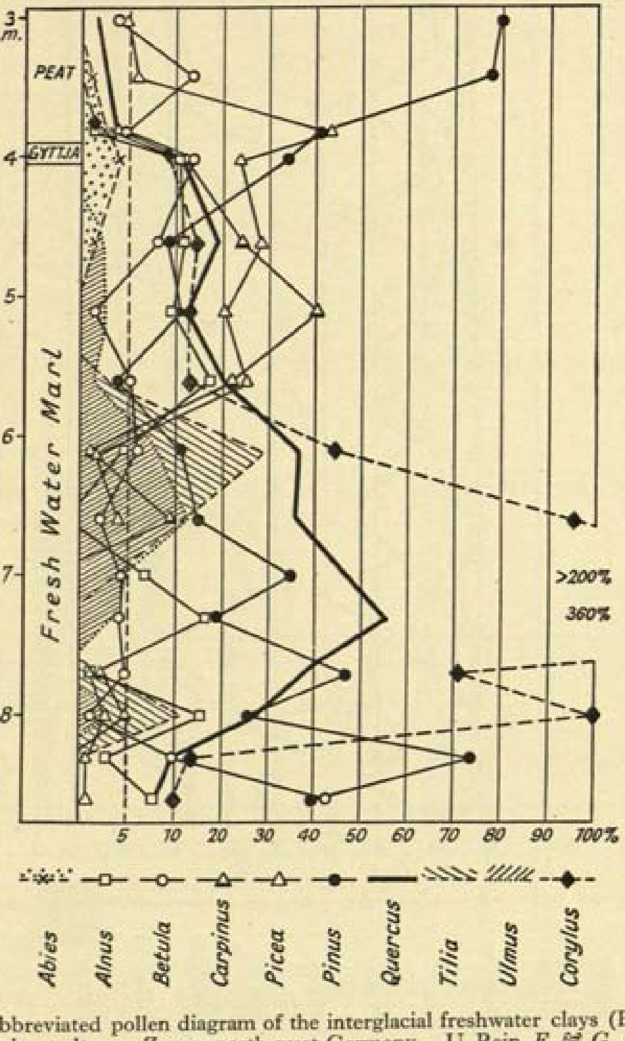

FIG. 172a.—Abbreviated pollen diagram of the interglacial freshwater clays (Eemian interglacial) at Godenstedt near Zeven, north-west Germany. U. Rein, *E. & G.* 1, 1951, p. 88, fig. 2.

excelsa and *Abies pectinata*; (*d*) *Quercus robur*, *Q. petraea* (*sessiliflora*), *Tilia platyphyllos*, *T. parvifolia*, *Acer platanoides*, *A. pseudoplatanus*, *A. campestre*, *Fraxinus excelsior*, *Fagus sylvatica*, *Betula pubescens*, *B. verrucosa*, *Alnus glutinosa* and *Corylus avellana*. These all disappeared and were replaced by a return of (*c*), (*b*) and (*a*) in this order, the succession opening and closing with a Dryas flora. Even the climatic periods of Blytt-Sernander (see p. 1472) and the Danish floral zonal succession (see p. 1445) are thought to

have been recognised.[160] Thus those of the Eemian interglacial have been numbered I to X or lettered *a* to *i* and nine zones (I to IX) have been recognised at Ohe–Munster (Brelie, 1954; Selle, 1954) which is placed in a short interglacial—there was no marine transgression between the Saale and Warthe (cf. p. 1166).

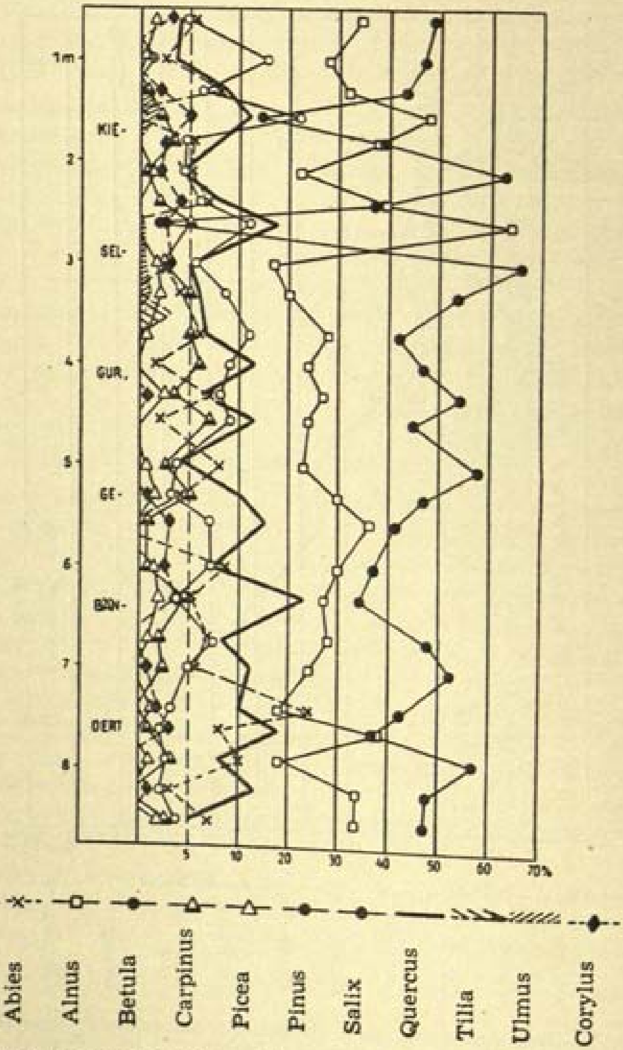

FIG. 172b.—Abbreviated pollen diagram from the banded Kieselgur (*Kieselgur, gebändert*) of Munster I (Saale-Warthe interval). P. Woldstedt *et al.*, *E. & G.* 1, 1951, fig. 4.

The postglacial events were in general paralleled, with the infilling of lakes, the formation of soil profiles, peat growth and marine incursions. The plant succession, however, was not always anticipated. Thus while in the post-glacial re-immigration the *Corylus* maximum was followed successively by *Ulmus*, *Tilia* and *Quercus*, the Danish interglacial order was *Ulmus*, *Quercus*, *Corylus* and *Tilia*,[161] and the dominant *Carpinus* of some places had no post-

glacial parallel.[162] The last interglacial pollen curve shows a double-peaked hazel and oak maximum.[163] *Abies* extended 300–400 km farther to the north-east in Poland than now[164]—the Saale-Weichsel interglacial in north Germany always has *Abies* in the transition from the *Picea* to *Pinus*, an earlier hazel maximum and copper beech in place of the hornbeam[165]—and *Carpinus* also spread farther eastwards. *Ilex aquifolium*, found both macroscopically and as pollen in Jutland interglacial deposits, is quite unrepresented in the

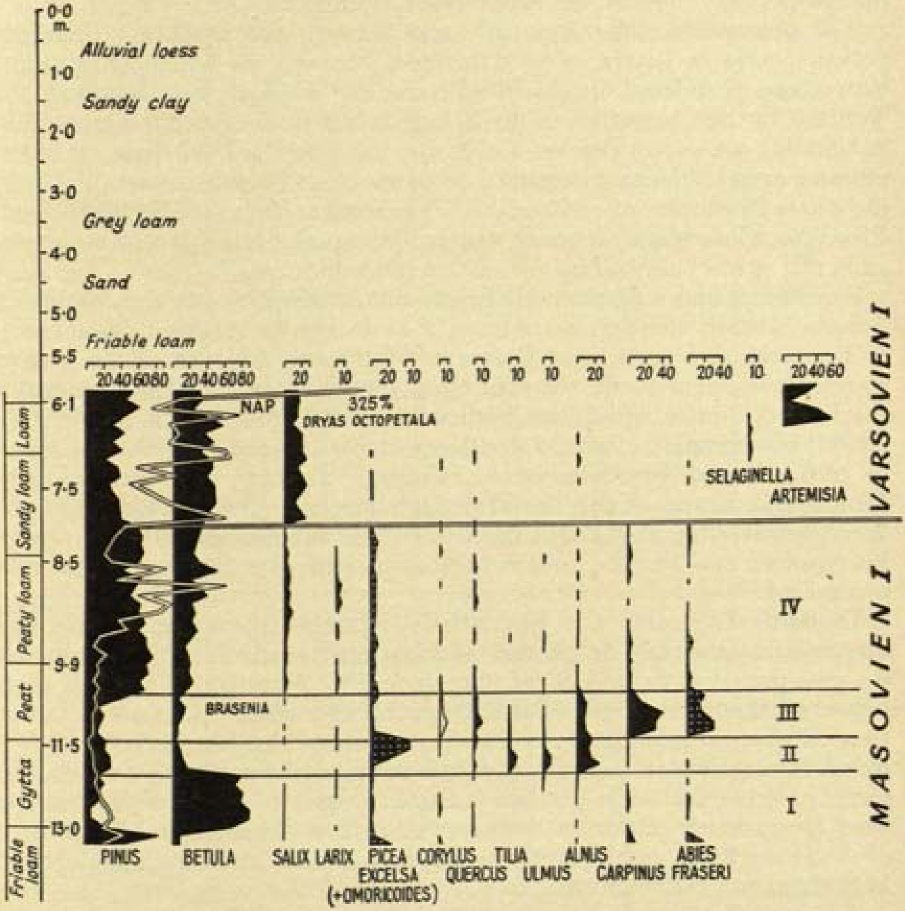

FIG. 172C.—Pollen diagram from the Masovian I interglacial at Nowiny Zukowskie, Poland. J. Dyakowski in W. Szafer, *Ann. S. G. Pol.* 22, 1952, p. 23, fig. 9.

postglacial deposits in Denmark.[166] In Jutland Bison was common and the Aurochs unknown in the last interglacial period while in postglacial time few bison have been found and Aurochs was plentiful.[167] During this interglacial there was also a wider distribution towards north-west Europe of *Picea* and *Abies*, a later spreading of *Corylus* and a substitution of *Fagus* of postglacial time by interglacial *Carpinus*—*Fagus*[168] was absent from west central

Europe. Each interglacial had a slightly different marine or plant composition[169]: they became successively colder[170] or shorter.[171] At Bilshausen, north-east of Göttingen, an interglacial belonging to the Cromerian had a succession which proceeded from birch and fir through EMW, beech EMW to spruce and pine and finally to fir and birch (Rein, 1955).

The first half of the succession sometimes lacks the later half,[172] as at Rabutz and Grodno and in the Eastern Alps. The Heligoland *Töck*, a clayey deposit found at a depth of 5–6 m B.S.L. which contains *Picea* and *Carpinus*, accumulated during the cooler pine and warmer mixed forest phase of an interglacial epoch[173] (cf. p. 1363), probably, since it is compressed like the Swiss *Schieferkohlen*, the Elster-Saale interglacial.[174]

The successions differ regionally and between one another. Thus the pollen spectra in Latvia shows differences between the Mindel-Riss, Riss-Würm and postglacial epochs.[175] Beech, *Fagus sylvatica*, is found in the Tertiary, in the Cromerian, in the *Schieferkohlen* of the Eastern Alps, and in Poland but not in the Tegelen, the Mainz basin or Pianico-Sellere, or in the ultimate or penultimate interglacial of Denmark and north Germany[176] or in the whole Pleistocene of Switzerland[177]; its absence from the Mindel-Riss and Riss-Würm interglacial deposits, except in the peripheral east and west, suggests that it was banished by the ice to a great distance.[178]

Some areas had a continental climate characterised by conifers, others an Atlantic climate with deciduous trees,[179] as during the last interglacial epoch in Denmark and north-west Germany[180] (possibly because of the greater marine inundation of the Eemian Sea), though Poland and Russia had a continental climate which was both drier and warmer[181] and an "eastern facies" of vegetation of mixed deciduous-coniferous forests with spruce and fir and pine and sometimes larch. *Tsuga*, a Tertiary relic, occurs in the Mindel-Riss but not in the Riss-Würm interglacial. The suggestion that the Weimar travertine shows that the Riss-Würm interglacial epoch in central Europe had two forest phases separated by one of steppe and loess[182] is unjustified.[183]

In north Germany, the Elster-Saale interglacial was apparently distinguished by the early distribution of *Picea* and by a double *Picea* advance in the pine period at the end of the interglacial.[184] *Picea* and *Abies* were more important than in the Saale-Weichsel epoch when mixed oak forest and hazel were distinguishing features. *Azolla tegeliensis* characterised the Günz-Mindel interglacial in Holland, *A. filiculoides* the Mindel-Riss,[185] though both forms have been found in one bed in that country.[186] *A. filiculoides* has also been found in the *Paludina* Beds (see p. 949), in the Baku and Singil Beds of the lower Volga and in southern England (Hoxne and Little Welnetham in Suffolk, and Birmingham).

An arctic horizon, if alone, may be interstadial or the early or late cold phase of a warm interglacial. Individual finds need to be treated with caution; *Betula nana* may occur in temperate interglacial floras[187]; *Elephas primigenius* may have had more thermophile members than the ordinary species[188]; and subarctic and temperate climates, as in profiles of the Danish Herning type, may alternate within a single interglacial epoch[189] (cf. p. 951). Fossil poverty, whether of animal or plant life, as in the case of the lake-sediments of the Inn and Isar (referred to the last interglacial epoch), may suggest an interstadial age.[190] Interbedded spruce and fir, which characterise subarctic forest and are common in both Europe and America, could have

lived close to the great ice-sheets and therefore do not prove an extensive retreat.

The difference between interstadial and interglacial may also be reflected in the soil profiles,[191] and in coastal regions, e.g. north Germany, by the absence or presence respectively of a marine horizon.[192]

Monoglacialism. Many European glacialists,[193] including workers in the French Alps,[194] and geologists in North America,[195] notably those whose field lay in the north or east of the continent where later drifts conceal earlier ones (see p. 976), admit marginal fluctuations but deny interglacial recessions: the glacial deposits were the product of an undivided Ice Age. The sceptics in all countries include those who accept elevation as the cause of glaciation (see p. 1536), just as believers in astronomical causes favour multiple glaciation.

The reasons urged against plurality are largely negative. The difference between the older and later drifts (see above) is not one of age but is owing to residual soils in the former[196] or to the different climates that obtained at varying distances from the ice-centres.[197] Similarly, oxidised layers between drifts do not signify climate but preglacial soils or materials weathered while undergoing transport on the ice,[198] or postglacial changes which depended upon the permeability of the drifts and the underground drainage.[199] The different composition of the tills was brought about by solifluxion,[200] by the upturning of marginal layers, as on the modern von Post Glacier,[201] Spitsbergen, or by depositing median and terminal moraines of different constituents, as in the Nordenskiöld Glacier.[202] The "upper boulder-clay" is often interpreted as the residual product of ice whose ground-moraine is the lower till[203] (see p. 383). The undermelt theory of R. G. Carruthers supports this origin (see p. 384); for in his view, for example, the drifts of Holderness (see p. 762) were the product of one glaciation, the Hessle Clay being merely an englacial horizon let down at the melting. Nevertheless, lake-deposits contain inclusions of till, below which the bedded deposits are rucked up, probably by icebergs; surface-melting far outweighs basal and englacial melting; and frequent oscillations of ice-fronts are normal rather than exceptional, so that the subsequent folding of frozen lake-muds may occur.[204]

The sandwiching of drifts with vegetation layers, the strongest argument for mild interglacial epochs, is circumvented by referring the fossiliferous deposits to a preglacial or a postglacial date[205] or by postulating interstadial oscillations[206] or successive invasions from different centres.[207] Wildkirchli (cf. p. 1034) was preglacial.[208] Most commonly, appeal is made to the old forests and soils associated with modern glaciers[209] or to the close association of vegetation with present ice-margins, of which instances have often been noticed since T. de Charpentier[210] first observed them in 1819. Many Alpine glaciers press down into the forest zone, as the following figures show,[211] the vertical distance in some cases being *c.* 1000 m and depending upon the reservoir's dimensions and the steepness of the glacier-bed.

Glacier	*Altitude of glacier-end*	*Altitude of neighbouring tree-line*
Bossons . .	1099 m	2300 m
Aletsch . .	1353 m	2300 m
Rhône . .	1760 m	2100 m
Morteratsch .	1923 m	2400 m

Thus glacier snouts are sometimes surrounded by vegetation in the Alps[212]; trees grow on the moraines of the Macugnaga Glacier on the east side of Monte Rosa[213]; wheat is cultivated close to the Aar Glacier[214] and rye by the side of the Findelen[215] and the Bossons Glacier[216] (this advanced into a forest in 1892); harvests are gathered about the Brenva Glacier[217]; and the Lower Grindelwald Glacier at its snout (1150 m) reaches the July temperature of 14·6°C[218] (cf. fig. 226). Wheat grows near Norwegian glaciers[219] and fruit and flowers within 2 miles (*c.* 3·2 km) of the ice in the Hardangerfjord[220] and *Ranunculus* and *Lotus corniculatus* flower within 9 m of the ice in the Bergen district.[221] Caucasian glaciers also end among vegetation[222] and Hooker[223] long ago remarked upon the proximity of ice and *Rhododendron* bushes in the Himalayas. Luxuriant vegetation has more recently been seen bordering the ice in central Asia[224] and living on moraine-covered parts of the Himalayan glaciers in Kashmir.[225] Glaciers enter deeply into the pinewoods in the Minya Gongkar region of Tibet,[226] and trees, bushes and flowers flourish in profusion in the ablation valleys of the Karakoram and Hindu Kush mountains.[227]

Contacts of this kind have been repeatedly noticed in Alaska[228]—the Malaspina Glacier was carpeted with dense forest of alder, cottonwood, spruce and hemlock as far as 20 miles (*c.* 32 km) above its end[229]—the sitka spruce and hemlock are up to 75 ft (23 m) high and 2·5 ft (76 cm) in diameter and 99 years old. Similar observations have been made on other Alaskan glaciers[230] and elsewhere in North America—the Nisqually Glacier on Mount Rainier makes a total descent of *c.* 10,000 ft (*c.* 3050 m), nearly 3000 ft (915 m) being below the timber-line[231]—as well as on the Veteran Glacier, Spitsbergen.[232] Birch grows close to the ice in the fjords of south-west Greenland (see p. 1388), and a fairly rich fauna and flora lives near the ice in Iceland.[233] Glaciers of the southern hemisphere descend to the sea through luxuriant evergreens and magnolias in west Patagonia[234] and are often hidden in New Zealand[235] by tree ferns, pine, beech and evergreen rain forest: the Franz Josef Glacier ends at 215 m A.S.L. amidst subtropical vegetation.

Monoglacialists contend that this intimate relationship held during the Ice Age; the periglacial tundra was so narrow that slight oscillations sandwiched glacial deposits with organic matter.[236] They point out that trees in south Greenland grow to 3–3·5 m high and that about 400 species of vascular plants are recorded from modern Greenland, of which 67% also occur south of the St. Lawrence and the Strait of Belle Isle, 24% in Massachusetts, Rhode Island or Connecticut, and 6% in Washington, D.C.[237] Accordingly, intermorainic vegetation does not necessarily imply interglacial oscillations.

Yet it is essential to distinguish between the climate at the margin of local mountain glaciers and that of vast ice-sheets on continental plains,[238] like those of Pleistocene Europe and North America. The difference is vital. In the first case, the climatic zones are superimposed vertically, so that only a small interval, measured in miles, separates the highest from the lowest—200 m of vertical distance in the Alps corresponds floristically to one degree of latitude in north Europe,[239] and on the Puna de Atacama and in central Asia the subnival touches the arid zone[240] and "glaciers dig their cool snouts into grey rocks blistering with the heat" (Rickmers). Contiguity of vegetation and glaciers, instanced above, occurs precisely where well-nourished glaciers penetrate zones to which they do not belong.

A. Hötting Breccia at 1,640 m and here 40 m thick—to the left, outcrop of Triassic limestone [H. Paschinger]

B. Hötting Breccia at 1,400 m ; lower part unbedded cone accumulation, above finely bedded banks [H. Paschinger]

A. Late-Pleistocene involutions (*Brodelboden*), Netherlands. Black, peat ; light colour, sand [R. G. West]

B. Dryas flora preserved in glacial clay, Colebrook, New Hampshire. Leaves include *Dryas drummondii* (A), *Salix reticulata* and *Vaccinum angustfolium* [R. J. Lougee]

By contrast, the treeless zone which isolated the ice-sheet from the temperate fauna and flora was very broad. This accords with general climatic principles[241] and is implied by the widely distributed Dryas flora of late-glacial time (see p. 1066) and by the arctic plants in interstadial deposits, as in north Germany (see p. 1168), which show the kind of vegetation we may expect outside an ice-sheet. Interglacial floras embrace plants which it is hard to imagine living near the ice (see p. 915). Temperate vegetation and ice were neighbours only where the conditions of modern Alaska, Patagonia or New Zealand were reproduced, i.e. where the vertical interval between the snowline and treeline was narrowest (see p. 1071) and a glacier could thrust its tongue into the lowest zone. Even in modern Greenland, where shrubs and trees grow close to the ice, the ice-edge is in the more genial climate near the coast. This was probably true of the Sierra Nevadas of California,[242] and the Pacific coast of Oregon and Washington,[243] of the Andes of South America,[244] of parts of Switzerland,[245] of the region east and south of the Alps[246] where the Illyric flora persisted[247] and the Piedmont and Lombardy glaciers and the Drau Glacier, as is proved by woody remains in the moraines and varve clays[248] (e.g. Paradiso-Noranco, Valtravaglia, Rè, Varese, Pianico-Sellere), advanced into an oceanic climate with forests of pine, birch and oak, lacking arctic plants. Vegetation grew on the moraine-covered ice[249] as in modern Alaska (see above). Coniferous forests clad the slopes of the Pir Panjal in Kashmir.[250]

Additional objections of a general kind have been raised against the polyglacial theory. The events of an Ice Age, it is held, would scarcely be duplicated with so nearly the same ice-limits[251] (cf. p. 924); there was only one period of cold mollusca and mammalia, the culmination of one long faunal change[252] (see p. 1031); and, as in the Mediterranean (see pp. 1090, 1271), only one cold marine horizon[253]; no species was evolved during the postulated interglacial epochs[254]; and only continuous ice in the Alps and Pyrenees could have barred the mammoth from Italy and Spain[255]—the discovery of this and other cold mammals in various parts of Italy (see p. 809) has deprived this objection of any force it may have had.

Equally ineffectual are the following contentions: glacial pressure and overfolding gave the apparent alteration of glacial and interglacial horizons[256]; the ice receded in the Baltic and about Lake Constance for tectonic reasons[257] and the classical fourfold succession of the Swiss schotter was of local significance and tectonically controlled[258]; glacial capture made possible the Dürnten and other Swiss lignites[259]; a lateral glacier advancing across an ice-free trunk valley sandwiched the Hötting Breccia between boulder-clays[260]; and the behaviour of the Rhône terraces admits only of the monoglacial view.[261]

Early monoglacialists evaded the difficulty which the warm trio presented by supposing that the characteristic member, the hippopotamus, lived in frozen rivers and had not the habits of the existing species,[262] alternatively that it frequented rapids which did not freeze over[263] or was protected from the cold like the mammoth and woolly rhinoceros[264] by a coat of fur or layer of fat as was its warm contemporary *Elephas antiquus*.[265] The Leeds (Kirkstall) hippopotami (see p. 1009) were postglacial.[266]

Although the cave lion and cave hyaena, which were definitely associated with cold animals (reindeer, musk ox, lemmings), may have evolved a protective coat,[267] this was most unlikely in the case of the members of the *faune*

chaude which were indisputably creatures of a warm climate and intolerant of cold.

Corbicula fluminalis, it is similarly contended, did not necessarily mean cool conditions[268] since this eurythermal mollusc lives to-day in snow-fed rivers in Sicily or in rivers in Turkestan which in winter are sheeted with ice for a few weeks or even freeze to the bottom.[269]

Early monoglacialists also had recourse to seasonal migrations of cold and warm faunas[270] like those which steppe animals make to-day[271] or the reindeer made in Magdalenian times—herds of this animal spent the winter in the Pyrenees and the summer in south Germany *c.* 2000 km away.[272] But such oscillations in general must have been secular or interglacial[273]; for the species embrace warm molluscs like *C. fluminalis, Belgrandia* (e.g. Weimar, Taubach, Phoeben, Klinge) and *Paludina diluviana* (including all stages from larvae to adult[274]) and warm mammals, e.g. hippopotamus, which do not migrate, as well as young individuals and others with milk teeth that were not seasonal visitors. The intermixture of warm and cold species, early stressed by W. Buckland and W. B. Dawkins, may have been owing to *remaniément*, to careless observation that did not discriminate horizons,[275] or to wrong identifications.[276] It may also have resulted from the mingling of biotopes (see ch. XLVII), for cold and warm forms doubtless mingled over an intermediate zone which moved northwards and southwards with the glacial and interglacial changes.

That the biotopes only became established in the upper Pleistocene and that the mammalian fauna shows the influence of the Glacial period only towards its close may be explained by the assumed smaller intensity of the earlier glaciations[277] and the greater length of the last glacial epoch (see p. 1031) or by the resilience of life and the adaptive powers of plants and animals.[278] Alternatively, the factors which favoured vast ice-formations were not necessarily those which modified and most strongly displaced life; dryness rather than cold has been invoked for the latter.[279] Without this acute climatic crisis the temperate fauna which had survived the previous cold period or periods might have lived to the present.

Extent of deglaciation. Evidence for successive glacial advances has necessarily been gathered in regions not far removed from the limit achieved by the ice. Tills and outwash sheets are here superimposed and have decipherable relations to one another and to the interglacial deposits. The extent of the deglaciation, however, is given by the distribution of the interglacial beds which range northwards in Europe into Denmark (*Nematurella* clay[280]) and Scandinavia (see p. 965) and in North America into Manitoba[281] and about James Bay (see p. 976). The nature of the interglacial life,[282] whether land mammals, land and freshwater molluscs, or plants, is a further indication: it implies temperatures even warmer than in the same regions to-day. Thus *Belgrandia marginata*, now confined in Europe to south-west France and Catalonia, in Pleistocene times ranged farther—to England, Denmark and Germany (Lüneburger Heide, Thuringia, Saxony, Swabia). The extent of the interglacial submergence is confirmative if it was owing to the return of waters previously locked up in the ice (see p. 1359): Ramsay[283] estimated the area of the world's ice during Tyrrhenian time at less than one-half of what it is to-day.

While many plants were subject mainly to edaphic factors (moor plants, for example, are little suited as climatic indicators since with them edaphic in-

fluences play a greater role) some of their distributions seem to imply a slightly warmer interglacial climate not only in oceanic but in continental regions like central Russia.[284] *Abies pectinata*, the European silver fir, limited to-day by the northern margin of the German Mittelgebirge, lived during the first interglacial as far as the lowlands of north Germany, e.g. at Winterhude near Hamburg.[285] Of similar significance are, for example, the plants in the interglacial peat of Saxony, denoting a climate equivalent to that of present-day Croatia and Transylvania[286]; the fossil remains of *Fagus sylvatica*, *Taxus baccata* and *Euryale ferox* (an aquatic herb very closely related to *Victoria*

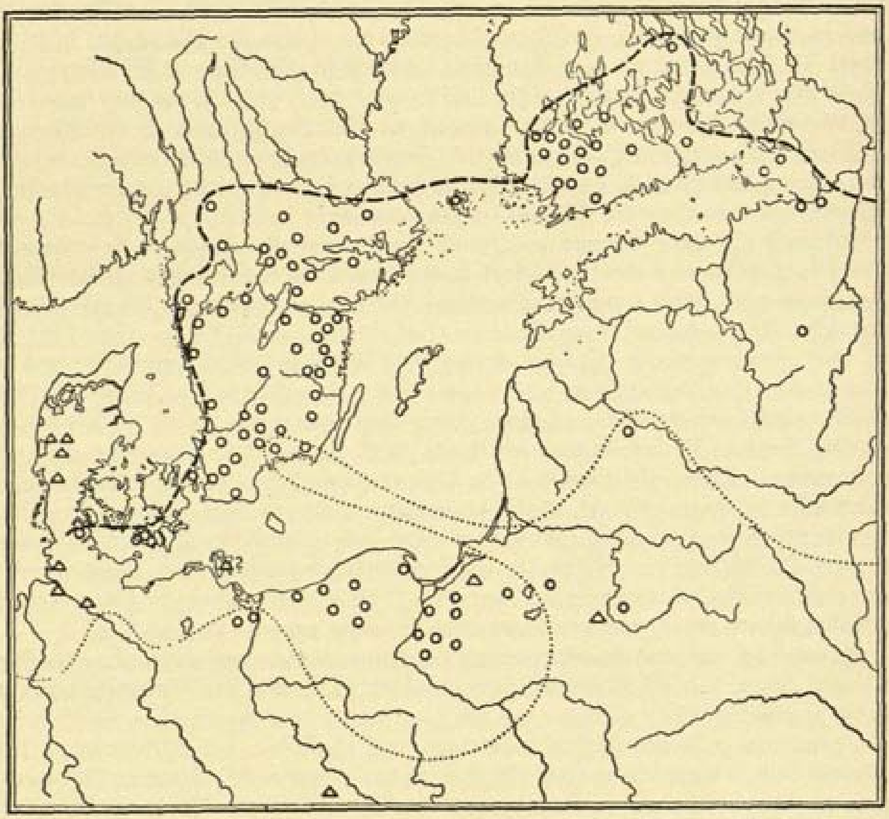

FIG. 173.—Distribution in the Baltic region of *Trapa natans* during interglacial, postglacial and historic times. K. Jessen and V. Milthers, *854*, p. 349, fig. 35.
△ interglacial localities O postglacial localities
– – – – – – – – northern limit during postglacial climatic optimum
················ northern limit in historic times

regia of India and eastern Asia) found in central Russia near the Oka River[287]; the presence of *Tsuga* cf. *diversifolia*, of Japan, in the Polish interglacial near Cracow[288]; the *Rhododendron ponticum* and *Buxus sempervirens* in Swiss interglacial beds (see p. 935); and *Ficus carica* which grew in northern France (Garcia, 1950).

A more extensive range is shown by *Trapa natans*, the water nut (fig. 173), whose northern limit in Germany now coincides with the July isotherm of 18°C[289]; by *Aldrovanda vesiculosa*,[290] *Acer campestre* and *Tilia platyphyllos*

which to-day extend to south Denmark and during the first interglacial epoch were dispersed over Jutland and north-west Germany. *Ilex aquifolium*, a decidedly Atlantic species in its present distribution,[291] was common in Europe during the last interglacial epoch when the climate was appreciably warmer and resembled that of Littorina time[292] (see p. 1303).

Mammalian distributions bear out these conclusions. While the *faune chaude* is missing from Scandinavia, *Elephas antiquus* has been found in moraines in north-west Russia and north-west Germany[293] (Neumark and Stettin). A molar also occurred in Fyn.[294] Mammoth has been discovered in at least ten localities in Fennoscandia (see p. 963), occasionally in Estonia and Latvia, more frequently in Lithuania[295] and East Prussia,[296] and in about 50 places, mainly within the area of the last glaciation, in Denmark,[297] with musk ox as in Sjaelland and north-west Jutland.[298] Although their provenance is insufficiently known and most were secondary, they do undoubtedly give a minimum extent of the deglaciation in north-west Europe. The absence of palaeolithic implements from the central regions, sometimes interpreted, e.g. in Britain,[299] as evidence of persistent ice, may only be because they are difficult to discover.[300]

Additional signs of a warmer climate are the interglacial plants in Russia[301] —some members of the broad leaf forest extended as far north as the White Sea during the long interglacial epoch—the higher treeline in Germany and the Alps,[302] the probably smaller extent of the tundra,[303] the westward extent of the tschernosem in Europe during the last interglacial epoch,[304] and in North America the animals and plants (see p. 973), including those of north California[305] where the isotherms were displaced 1500 miles (*c.* 2400 km) during the San Pedro stage. Molluscs, both fluviatile and marine, are corroborative. *Corbicula fluminalis* in Germany means a higher temperature, especially in winter,[306] while the marine molluscs in Spitsbergen,[307] in the Eemian Sea (see p. 946) and Boreal Sea (see p. 959), in California[308] and eastern North America,[309] and in the southern hemisphere, e.g. Patagonia,[310] are only consistent with warmer waters. The interglacial sea of Cape Nome, Alaska, for example, was 4·4°C warmer than the present Bering Sea.[311]

Europe's *faune chaude* is incompatible with a climate less warm than to-day. *Cervus dama*, a Mediterranean deer, in Danish interglacial deposits has the same significance.

From the palaeontological evidence just outlined, we deduce that the climate was warmer and roughly that of the postglacial Climatic Optimum (see p. 1493)—the air in Jutland and north-west Germany during the last interglacial epoch was 2°C warmer than now during the hottest month[312] and in central Europe was at least 1·5–2·0°C warmer during January.[313] Insects from the interglacial beds of Sweden bear the same testimony.[314] Along the seaboard, as in Jutland,[315] the humidity was unmistakably higher. This agrees with such physical evidence as the nature and depth of the interglacial weathered zone.[316]

While all glacialists concede important and repeated oscillations and intermittent glaciation in lower latitudes, they disagree widely concerning the importance, magnitude and duration of the intermittence and about the continuity of the ice. The nearer we approach the ice-centres, the less satisfactory the evidence of the interbedded fauna and flora becomes. This perhaps explains why workers near the glacial peripheries believed in recurring glaciations and intervening warm episodes while their contemporaries,

investigating the more central parts which may have never been deglaciated and in any event had fewer advances and recessions, generally accepted the unity of the Glacial period.

Complete deglaciation. Although the times of retreat, like the genial present, do not need to have been aglacial to be truly interglacial,[317] complete deglaciation has been frequently postulated.[318] It is not merely on the broad principle that mild epochs and extensive ice-sheets in middle latitudes are mutually contradictory, but for one interglacial at any rate on very good physical and palaeontological grounds. The deep and intense weathering of the drifts and older loess—this *argile rouge* on the older loess of west Germany and north France indicates dry summers with temperatures slightly higher than the present; the nature of the plants in the Scandinavian interglacial deposits (see p. 964); the occurrence of the mammoth in Scotland and Ireland (see p. 809) and in Scandinavia (see p. 963); the wider distribution in Europe of *Ilex aquifolium*, *Tilia caucasica*, *T. platyphyllos*, *Fagus sylvatica*, *Acer tataricum* and *Taxus baccata*[319]; the assemblage of plants at Gort, Co. Galway,[320] viz. *Rhododendron ponticum*, *Pinus sylvestris*, *Picea abies*, *Abies alba* and *Erica mackaiana*; and the warmth and extent of the interglacial seas including the Eemian Sea (see p. 946) and the Boreal Sea (see p. 959) (on the assumption that waters had previously been locked up in the ice), together with some of the data set out above—all these seemingly admit of no other conclusion than that Scandinavia was completely ice-free during one interglacial epoch[321] and Europe had less ice than now.

This held for the whole of the continent,[322] including the Alps (occasionally denied[323]). Here, the Pontic plants, limited as now during the Riss-Würm interglacial by the Eastern Alps and the boundary of the Alps and the Karst, crossed the North Tyrol Limestone Alps.[324] Pleistocene mammals like cave hyaena, cave bear and cave lion lived in high-level caves, e.g. Wildkirchli and Drachenloch, the highest prehistoric station in Europe (see p. 800), and mammoths wandered deep into the Alpine valleys, as near Kufstein and Innsbruck in the Inn (see p. 809). The air was warmer by 2·5°C[325] and the snowline was consequently higher[326]—the occurrence of *Pinus nigra* (found to-day in the Balkans and Pannonic basin) in Drachenhöhle signifies 400–600 m higher.[327] The humus in this and other high Swiss "alpine palaeolithic" caves (see pp. 800, 1035), and the mammalian fauna which suggests forests are confirmation[328] (cf. p. 1034). Conditions were favourable to life, since, for example, the cave bear rarely had deformed bones.[329]

The interglacial beds, particularly those of Toronto and the lignites of Moose Creek (see p. 976), situated less than 300 miles (480 km) from the Labrador ice-centre, as well as evidence of a marine submergence in the James Bay region,[330] seem to imply a complete deglaciation of North America[331]—glaciers may have persisted on the higher parts of Alaska and the beds themselves may be lateglacial,[332] while the two North Pacific species, *Serripes laperoussii* and *Macoma incongrua*, found in an interglacial bed at Sankaty Head in New England, suggest that the North-West Passage was more open than now.[333] The Caucasus and Kashmir–Himalayas also had a long second interglacial.[334]

Polar evidence is singularly scanty. Iceland[335] may then have had little or no ice to judge from the composition of the fauna in the interglacial marine deposits of Fossvogur and Snaefellnes, from the extent of the igneous intrusions, and from the woods of alder, birch and willow far inland—alder

has not lived in postglacial Iceland. That Greenland and Antarctica lost their ice-sheets[336] (see pp. 679, 902) is unlikely and incapable of direct proof, though physiographic evidence, including valley profiles and peculiar plant distributions, point, it is suggested, to a bipartition in Greenland[337] (see pp. 900, 923)—ancient moraines contain calcareous concretions with marine animals and pollen of numerous plants including *Alnus* which makes up about 30–35% of the total pollen and indicates a climate considerably warmer than that of to-day (Bryan, 1954)—and a full succession of four glacial epochs has been registered in sediments flooring the Ross Sea.[338] In both regions, where the lowering of the ice-surface may have been 60–120 m,[339] determinations of multiple glaciation are made virtually impossible by the almost total lack of moraines. According to Milankovitch's calculations,[340] the Antarctic ice at no time melted away completely during the Quaternary: in 75° S. Lat. seventeen long periods of intense minima of summer radiation alternated with as many short periods of weak maxima. The oscillations on such a high polar continent were probably smaller: greater warmth increased the precipitation (see p. 641), and the long travel of the ice (see p. 104) prolonged the glaciation.

Climatic curves. The interglacial epochs had different degrees of warmth and duration. Yet in all cases, as in the Toronto interglacial,[341] they were many times longer than the postglacial period (see ch. L). This is proved by the amount of denudation, as in the Baltic region[342]; by the magnitude of river-action in Kashmir[343] and in Tasmania where rock gorges, 300–600 m deep, were cut during the Malanna-Yolande interglacial[344]; by the great size of the Mindel-Riss interglacial series in various parts of the Alps, especially in limestone areas[345]; or by the degree of weathering of the drifts, a method used for instance for the Alpine glaciation.[346] M. Giesenhagen's application[347] to the north German interglacial (Saale-Weichsel) Kieselgur of F. Nipkow's discovery[348] that the darker and denser layers of Zürich See sediments were deposited in winter and the lighter ones in summer, and his calculations of 11,000–12,000 years for this interglacial fraction, point in the same direction.

Notwithstanding the great or even insuperable difficulty of ascertaining the relative and absolute lengths of the glacial epochs, those who accept multiplicity or favour astronomical causes of the Glacial period (see ch. LI) generally (though not unanimously[349]) believe that the interglacial epochs exceeded the glaciations in duration. This is suggested by the great depth of weathering of the older loess, the nature and abundance of the interglacial life, the wide interglacial platforms of marine erosion, and the general absence of terminal moraines about the older drifts.[350] American glacialists[351] make the interglacial epochs roughly four times the 80,000–100,000 years assigned to each glaciation, or 25 times the glacial culminations. This relationship, together with the warmth of at least one interglacial epoch, has prompted the paradox that the glaciations were merely abnormal episodes[352] in a "Genial" or "Miothermic" period.[353]

The temperature curve, smoothed of the oscillations which on the analogy of the postglacial oscillations (see ch. XLII) doubtless crinkled them, has been drawn for the Alps by Penck[354] (fig. 174) and by Heim[355] (fig. 175)—this was based on the state of erosion and weathering of the various drifts and agrees apparently with the amount of lowering of the Alpine valleys during the several glacial epochs.[356] While Penck's curve gives the relative lengths

of the interglacial curves as 3 to 12 to 1, a curve for the Himalayas[357] shows 4 to 5 to 4, and for East Anglia[358] (Cambridge), 128, 103 and 65. The relation of the great interglacial to the last interglacial was estimated at 2:1 by Eberl, 1·5:1 by W. Soergel, and 3:1 by Milankovitch. Geological confirmation of the latter's astronomical sequence of minima of summer radiation (see p. 1544), which it is claimed gives the relative and absolute lengths of each of the glacial and interglacial oscillations, has been sought in the *Vollgliederung* of the Quaternary—the warm phases between the double or treble phases (of which the second in each "group" is usually the greater) are termed interstadial, those between the glaciations being called interglacial. The *Vollgliederung*, which is really a refinement of Penck and Brückner's scheme (see p. 933), is seen in the glacial succession of east England,[359] Holland[360] and Italy[361]; in the drifts of Germany[362] (Thuringia, Rhine, Silesia), Poland,[363] Russia[364] and the Alpine glaciation,[365] including the classical area of Penck's investigations in the Iller and Lech where, palaeontological and

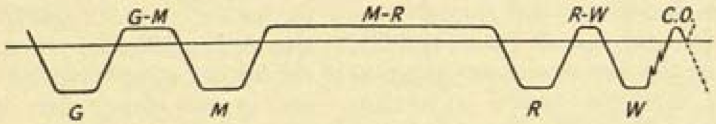

FIG. 174.—Penck's curve of the Alpine glacial and interglacial epochs, modified. J. K. Charlesworth, *Sc. Pr.* 41, 1953, p. 4, fig. 2.

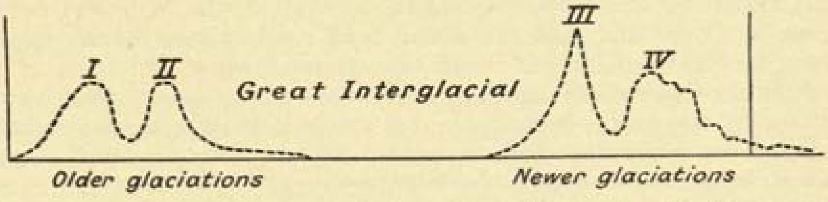

FIG. 175.—Heim's curve of the Alpine glacial and interglacial epochs. Ordinate, extension of glaciers; abscissa, from end of Tertiary to Recent. *732*, p. 344, fig. 57.

petrological means failing, the subdivisions are based upon the number and height of the schotters and upon their loess and loess loams; in the terraces of the Thames[366] and the Somme[367]; in the terraces and tectonic movements of the Ilm, Werra, Weser, Saale and other rivers of central Germany[368] from the Rhine (including its tributary the Neckar) to the Oder, where, following Soergel, three terraces of Würm age and two terraces belonging to each of the Günz, Mindel and Riss glaciations are recognised—some of the six "preglacial" terraces may represent the Danube or earlier glaciations[369]; in the periglacial terraces of Czechoslovakia[370]; in the *Verlehmungszonen* of the German, Austrian, Czechoslovakian, Hungarian, Russian, Rumanian and Bessarabian loess[371]; in the interglacial profiles of Ehringsdorf[372] and the double character of both the Swiss Deckenschotter[373] and the other Alpine glaciations[374]—the Riss is said to be double[375] or triplicate[376] in south-west Germany and the Würm double in the Balkans[377] and Thuringia[378]; in the Pleistocene deposits of Alsace[379]; in the four summer minima of decreasing

intensity suggested by the erosive features and humid conditions associated with the Kharga Oasis[380]; in the terraces of the Ebro[381]; and in the fluctuations of sea-level,[382] including those of Morocco and the Pleistocene raised beaches, seventeen in number, of South Australia. R. Spitaler's astronomical calculations[383] also gave two peaks to each of the older glaciations and three peaks to the last glaciation.

Soergel[384] has essayed the construction of a *Vereisungskurve* based upon the effects of solar radiation, caloric properties of the ice, retardation and other relative factors, and in 1939 postulated Donau (Danube) 1, 2, 3, Günz 1 and 2, Mindel 1, 2, 3, Riss, 1, 2, 3 and Würm 1, 2 and 3 stages. It is doubtful, however, whether purely thermal curves can be expressed in glacial phenomena in this way since the temperatures along the ice-edge are much modified by the ice itself[385] (see p. 676), and glaciations and recessions lagged behind the temperature changes.[386]

The shape of the curve about a glaciation is unknown. It may have been symmetrical[387] or asymmetrical with a steep fall before glaciation.[388] Much more probably, as is suggested, for example, by the stratigraphical relations of the loess and by the widespread decay of the ice during the final stage,[389] it portrays a slow advance of glacial conditions and their rapid disappearance,[390] though the tendency to self-perpetuation of the ice (see p. 678) has led to the suggestion that the period of melting was several times that of the ice-formation.[391]

We are still some distance from the time when the number of glaciations can be stated with certainty. The two, three or four glaciations suggested for most parts of the world have been affirmed by explorers who are not glacial specialists and whose investigations were of the nature of reconnaissances. Unanimity has not nearly been reached (see below) even in regions like Switzerland and north-west Europe where hundreds of researchers have been examining countless sections during more than a century. Nor is it by any means improbable that the general retrogressive series of glaciations one within the other was preceded by a similar progressive series, either no longer visible or subsequently destroyed[392]: the Günz, Donau and Elbe glaciations may be the last of such a series. Tentative supporting evidence[393] has been cited from the loess of Hungary and from the periglacial terraces of Germany. Climatic oscillations in the upper Pliocene[394] seem to suggest that these pulsations began even earlier. At least five pre-Nebraskan ice-epochs are thought to be represented in the oceanic deposits of the east Pacific Ocean (Arrhenius, 1952).

Number of glaciations. Critical opinion is at present overwhelmingly in favour of oscillations of interglacial magnitude. Upholders of monoglacialism are becoming fewer, and discussion is turning more and more upon the number of the epochs rather than upon the question of their existence. Nevertheless, one glacial epoch only, with retreat phases, has been demanded on field-evidence for the Riesengebirge, Portugal, Apennines and Balkans in Europe,[395] for various Asian regions,[396] e.g. Caucasus, Tien-shan, Alai and Altai, west Turkestan and north Siberia, for Kilimanjaro, Ruwenzori and the Andes in the tropics,[397] for north-east Nevada in North America,[398] for Hawaii,[399] for Spitsbergen,[400] and for the present heavily glaciated Antarctica and Greenland[401] (see below).

Three glacial epochs, one often less definite than the other two, have been described for Dombes,[402] L'Aubrac,[403] Auvergne and Cantal,[404] Vosges,[405]

Tatra,[406] Hungary,[407] north Albania,[408] Russia[409] and Iceland[410] in Europe; for the Altai,[411] Kuen-lun,[412] Himalayas,[413] Lena-Aldan plateau,[414] north China,[415] north Siberian coast[416] and New Siberian Islands in Asia; for Arizona,[417] Colorado,[418] California,[419] Utah,[420] Wyoming[421] and Montana[422] in North America; and for Patagonia,[423] Cordillera Real[424] and Tasmania[425] (= Malanna (ice-sheet), Yolande (cirque-glaciers) and Margaret (mountain-tarn phase) glaciations) in the southern hemisphere.

Quadriglaciation, the result partly of a too rigid alpino-centric standpoint, has been claimed for the Balkans,[426] Vosges,[427] Black Forest,[428] Pyrenees (see p. 938), Apennines,[429] Liptau Alps,[430] Tatra[431] and Corsica[432]; for China,[433] the Caucasus,[434] Pamirs,[435] Kashmir,[436] Karakoram and Himalayas[437]; for Hawaii,[438] Alaska,[439] Sierra Nevadas and Basin Ranges of North America[440]—these have been termed in the order of decreasing age the McGee, Sherwin, Tahoe and Tioga stages[441] (the last two may belong to one epoch); for South America,[442] Bermuda,[443] Australia and Tasmania[444]; and are implied in the interglacial origin and triple nature of the Norwegian strandflat (see p. 1250) and in the four physiographical cycles of China.[445] Astronomical curves[446] (see p. 1544) suggest, as did Eberl's glacial researches,[447] that each glaciation was double except the last which was triple.

Four glacial layers, identifiable chemically and mineralogically and by their pelagic foraminifera and ostracods in cores up to 19 m in length, have been found in the Atlantic Ocean west of the Dolphin Rise[448] by an explosive type of sounding apparatus which fires a tube into the bottom deposits and draws a core[449] (fig. 176). The coring done to date is largely in the nature of a reconnaissance. During the cold periods, colder forms, e.g. *Globigerina bulloides* and *G. inflata* replaced *Globorotalia menardii*, red clay replaced globigerina mud (especially east of South America), and the distribution of TiO_2, MnO, Fe_2O_3 and P_2O_5 was altered. The cold layers may correspond to four glaciations or they may be the equivalent of four substages of the last glaciation or of maximum glaciation.[450] The cold horizons in equatorial regions of the Atlantic have been assigned to Würm 1, 2 and 3 and the Riss.[451] Cores in the floor of the Arabian Sea also give four cooler horizons characterised by *Globigerina bulloides*, the intervening warm layers having *Globorotalia menardii*.[452] The subarctic foraminifera in cores in the Caribbean Sea reveal four cold horizons (with substages) and one long (Mindel-Riss?) warm or interglacial epoch.[453] Cold layers, with an interglacial horizon, have been found in cores in the Mediterranean (see p. 1025) and cold layers, indicated by red clay, low in carbonate, in the south-east Pacific (see p. 1094). The full sequence of glacial epochs is thought to be recognised in the bottom deposits of the eastern Pacific Ocean (Arrhenius, 1952).

Five alternations of emergence and submergence during the Glacial period are suggested by tilted surface-terraces and by the evidence of wells in the Mississippi delta.[454]

J. Geikie,[455] a constant advocate of multiplicity, postulated six glaciations, named Scanian, Saxonian, Polandian (amended in 1914 to the more euphonious Polonian), Mecklenburgian, Lower Turbarian and Upper Turbarian, separated by interglacial epochs styled Norfolkian, Helvetian (= Tyrolean, 1914), Neudeckian (= Dürnten, 1914), Lower Forestian and Upper Forestian. This classification, though seemingly representing the polyglacial hypothesis in its extreme form, is really only fourfold: the Lower and Upper Turbarian glaciations, if they existed at all, were stadial only,[456]

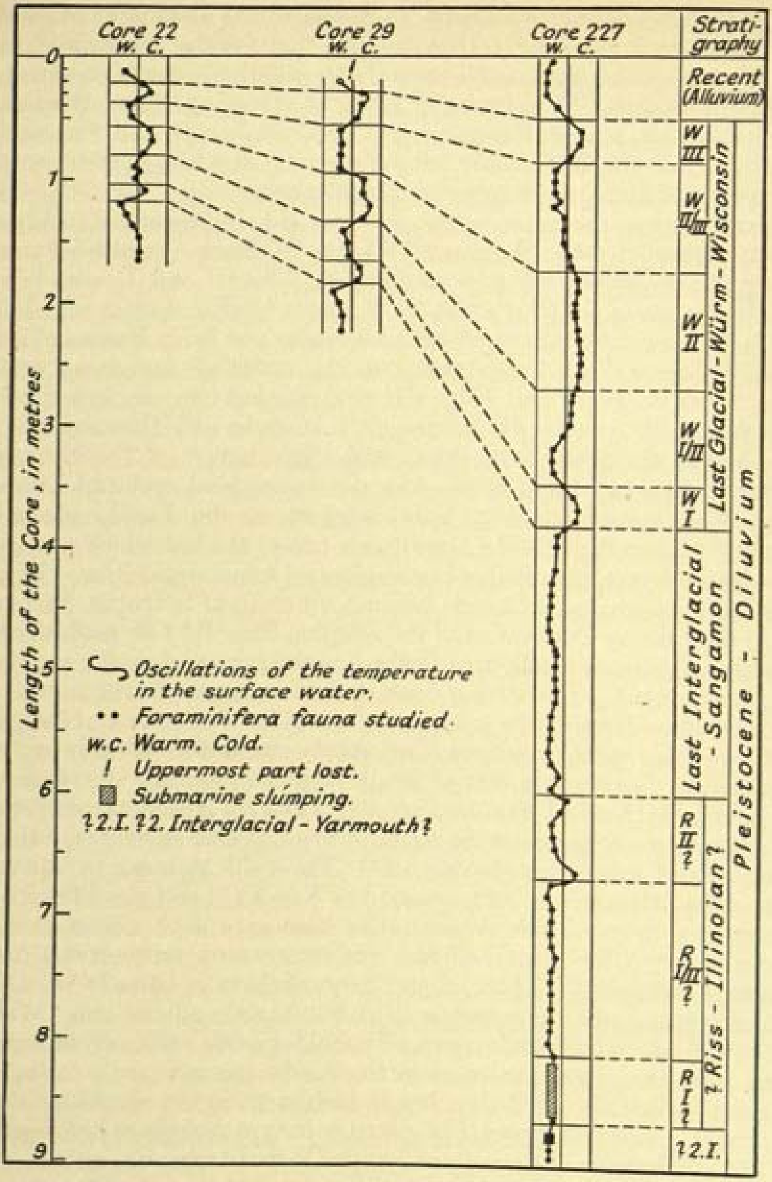

FIG. 176.—Biostratigraphical structure of three *Albatross* cores in the North Atlantic. W. Schott, *Göteb. Vet. Vitt. H. B.* 6 (2), 1952, p. 9, fig. 3.

equivalents possibly of the Gschnitz and Daun stadia of the Alps,[457] but are in all probability to be equated with the Atlantic and Sub-atlantic periods, just as the intervening Lower and Upper Forestian belong to the Boreal and Sub-boreal periods.[458] Six glaciations have, however, been postulated more recently for Germany (see p. 941), for the Niemen basin and Poland[459] (the glaciations are denoted Old Glacial, Carpathian, South Polish, Central Polish, North Polish and Baltic) and for both east and west Europe.[460] An even greater number is required by Milankovitch and his supporters (see p. 1544).

Evidence of biglacialism is widespread. It has been claimed from field-evidence in all parts of the world, as for polar regions, e.g. Faeroes[461] (peats, molluscs and consolidated moraines), Iceland,[462] Spitsbergen,[463] Franz Josef Land,[464] Novaya Zemlya[465] and Greenland[466]—because of its twice-eroded cirques near the Arctic Circle and their relative altitudes, its so-called interglacial peat (see above), its stream-erosion between two glaciations in the east and different states of weathering (see p. 918)—for middle latitudes, e.g. in Europe, Carpathians[467] (interglacial deposits as yet unknown), Hohe Tatra,[468] Apennines,[469] Pyrenees,[470] Vosges,[471] Black Forest,[472] Bavarian Forest,[473] Bohemian Forest,[474] Riesengebirge,[475] Spain,[476] Balkans,[477] Britain[478] and Scandinavia[479]; in Asia, e.g. Caucasus,[480] west Pamirs,[481] Tien-shan,[482] Alai,[483] Altai,[484] China,[485] north of the Gobi desert,[486] and central Asia generally[487] and Siberia[488] (on the evidence of the two layers of ground-ice (see p. 565), parted by a vegetation layer with shrubs and elder, white birch, and bones of mammoth and woolly rhinoceros equated with the Alpine Riss and Würm[489]). Duality has also been averred for North America, e.g. Alaska,[490] British Columbia and northern Rocky Mountains,[491] Cascade Range of Oregon,[492] Colorado[493] (including San Juan Mountains), Big Horn Mountains, Wyoming,[494] and the mountains of Montana,[495] Idaho[496] and California.[497] A double glaciation was apparently general in the Andes,[498] as is demonstrated by outwash, moraines, loess and the double level of the lakes on the plateaux,[499] and established for Ecuador, Bolivia, Peru, Chile, Argentina, Patagonia and Tierra del Fuego. It also characterised South Georgia,[500] New South Wales (Riss and Würm),[501] Tasmania,[502] New Zealand[503] and East Africa.[504]

Although there may have been a fourfold glaciation in both Europe (see p. 933) and North America (see p. 968), there may have been only one complete deglaciation, the other two interglacials being rather of the nature of large oscillations. Bayer,[505] championing this view and reverting in some respects to the opinion of A. Escher v. d. Linth and O. Heer, linked the Günz and Mindel and the Riss and Würm into two glaciations, more or less symmetrically disposed about the great Mindel-Riss interglacial, and reduced the Riss-Würm interglacial to 10,000 years only. Others have supported him.[506] In favour of bipartition have been cited the occurrence of only one period when the ice melted completely from Europe (see above), including the ice-centres of Scandinavia, the Alps and the British Isles, and from North America (see above), and the single warm marine transgression, the Eemian of Europe (see p. 944), the Boreal Sea of northern Eurasia (see p. 959) and that of North America (see p. 977). There existed only, as in coastal California, two cold horizons in the marine deposits[507]; two withdrawals of the sea corresponding to the oncoming of two glacial epochs[508]; and (according to some), two pluvials, each the equivalent of a glaciation or twin glaciation (see ch. XLI). There was no marked faunal reaction which would correspond to a third (Riss-Würm) full, warm interglacial. Where four glaciations are postulated, it is generally the second or middle glaciations, as in the Himalayas,[509] which are the longest. While in Germany, the "great interglacial" may be represented by sediments 40–50 m thick, as at Quakenbrück and in the lower Elbe, those of the last interglacial, as in Denmark, were only 4 m thick.[510]

Bearing in mind the conscious or unconscious influence of the Alpine classification and the tendency to confuse minor variations or retreat phases

with oscillations of interglacial magnitude, definite evidence cannot at present be said to exist for more than one long interglacial epoch. The Alps themselves are perhaps unsuited to give the scale of Pleistocene climatic changes and are an insecure foundation for a fourfold glaciation, not only because of the doubts that have been cast upon this in the Alps themselves (see p. 937) but because they are peripheral and mountainous. Even in the Alps, the classical region of four glaciations, there is only one outstanding interglacial epoch, though the last interglacial epoch may have been warmer than now.[511]

Work on radiocarbon, on the distribution of isotopes and on ionium in ocean cores will in the future give a knowledge of the changes of temperature in the Quaternary and of their dates.

Similar glacial distributions. A remarkable fact which a careful examination of the extents of the various glaciations in Europe (fig. 188) and North America (fig. 196) brings out is the close similarity in the extent of the ice-sheets at the different glaciations (see p. 1541)—this is well seen in the known and inferred southern limits of the Kansan, Illinoian and Wisconsin ice-sheets respectively; the borders are broadly parallel, though the Kansan drift extends notably beyond the others in Nebraska, Iowa and Missouri, the Illinoian drift in Illinois and Indiana and the Wisconsin drift in the Dakotas. The near congruence of these several drifts resulted in part from the topographical barriers of the Driftless Area of Wisconsin and of western Pennsylvania (Alleghany Plateau), both of which opposed the glacial advance.

It seems probable, however, that the nourishment, wastage and discharge and the physical conditions for the origin of the ice-sheets were repeated with each glaciation,[512] and that the ice-sheets originated in the same districts, developed in the same way and were governed at the maximum by the same physical and climatic controls. Thus the shift of the area of radial outflow recorded in the drifts of the last glaciation in Denmark (see p. 1168) is similarly recorded by the erratics of the earlier glaciations.[513] The ice-sheets were hovering near equilibrium in each case when the climatic conditions were reversed.

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Chapter XXXVII

PLEISTOCENE STRATIGRAPHY: REGIONAL SUCCESSIONS

1. *Alpine Glaciation*

Earlier work. Morlot's suggestion of a double glaciation for Switzerland (see p. 898) was adopted by C. Deicke, O. Heer, A. Baltzer and A. v. Wettstein on palaeontological grounds (see p. 935) and by A. Favre[1] and F. Mühlberg,[2] the latter confirming his observation that a schotter horizon separates the moraines. Penck[3] found three glaciations in Bavaria and around Lake Constance corresponding to three schotters which he named *Deckenschotter*, *Hoch-* and *Niederterrassen*. They were later recognised in the Salzach by Brückner[4] and in Switzerland, e.g. about Basle, by du Pasquier,[5] who styled the three glaciations *paléoglaciaire*, *mésoglaciaire* and *néoglaciaire*. A. Gutzwiller[6] discovered that the Deckenschotter near Basle was double, thus raising the number to four. Penck's attempt[7] to explain Gutzwiller's two levels by dislocations was short-lived; for two years later in his classic work he himself adopted and developed the fourfold classification,[8] subdividing his original Deckenschotter into an older and a younger Deckenschotter.

The Deckenschotters are consolidated and deeply weathered and are calcreted, as in the north Italian *ferreto*[9] and in localities where they provide building stones. Yet the degree of rotting of the boulders depends upon the composition, surface configuration and drainage. The Terrassenschotters are generally unconsolidated, little weathered and only calcreted if limestone constituents are abundant. They enclose boulders of the Deckenschotter[10] and are more gently inclined than this,[11] the difference in gradient among the Terrassenschotters themselves being much less than that between the Deckenschotter and Hochterrassenschotter.

The Older Deckenschotter forms sheets or *Decken* or isolated plateaux or hills, and into them the Newer Deckenschotter has been sunk. The Terrassenschotters, as their names imply, build terraces along the principal valleys. Yet they are seldom symmetrical, Hochterrassenschotter usually fringing one side of the valley and Niederterrassenschotter the other, so that four steps on one side are rarely seen. Sometimes the schotters are superimposed,[12] as near München and in the Po Plain, but generally, as in Swabia and Upper Austria, have cut through the older formations (fig. 177). This *emboîtement* occurs where interschotter erosion was great, superposition characterising valleys in which accumulation equalled erosion[13] or ridges exerted a stau-effect[14]: the lowering of the floor in the Rhine rift valley facilitated the *emboîtement* in the north while stability of the erosion basis favoured the piling up of the schotter in north Italy.[15]

The schotters often lie in detached fragments, crowned by hamlets or villages. Their reconstruction is only possible by following their gradients and uniting the fragments into continuous profiles. To be conclusive these must be checked by the composition and the state of weathering, by the contained fauna, by the relationship to the loess, and by allowing for subsequent

tectonic movements.[16] The succession is occasionally supported by the tills, as in Tyrol, where three tills with interbedded fossil-bearing interglacial deposits occur.[17]

Penck's scheme. The scheme of Penck and Brückner[18] was based upon the schotters and the relation of these and of the associated moraines to the loess and fossiliferous deposits. It established four glaciations for the Alps. These were termed Günz (= Older Deckenschotter), Mindel (= Younger Deckenschotter), Riss (= High Terrace) and Würm (= Lower Terrace), the names, bearing initials alphabetically arranged, being those of four tributaries of the Danube near Ulm on the Iller-Lech plateau of Bavaria. This classification, in which the interglacial epochs are designated by hyphenating their

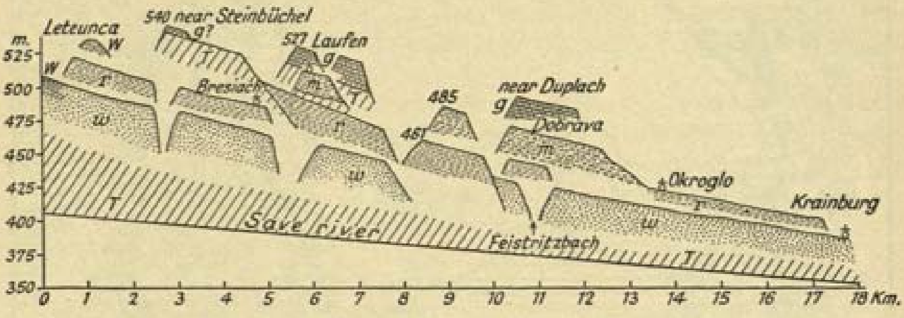

FIG. 177.—Longitudinal section through the Save Valley showing four schotter terraces (Günz, Mindel, Riss, Würm). Height fifteen times horizontal scale. T = bedrock. A. Penck, *1297*, p. 1053, fig. 127.

adjoining glacial epochs, namely, Günz-Mindel, Mindel-Riss, Riss-Würm, is the ruling one in Europe, having superseded the prior nomenclature of J. Geikie (see p. 921), probably because its nomenclature is simpler and shorter. "Cromerian" (C), "Dürnten" (D) and "Eemian" (E) have, however, been suggested for the three interglacial epochs (see p. 953).

The extent of the various Alpine glaciations is given in fig. 130, p. 716. The Günz glaciation is mainly recognised by its schotter since, as a rule, it kept within the Würm limits. Günz moraines have, however, been definitely noted in the terrain of the Iller, Rhine and other glaciers[19] and in the lee of projections[20] in the Isonzo and in several other places.[21]

The Mindel was the maximum in the east, the Riss in the west (see p. 1041). The Würm was much smaller; on the north, the difference in area between the Riss and Würm glaciations decreased from 1·5:1·0 in the Rhône to 1·4:1·0 in the Linth and 1·3:1·0 in the Rhine[22]; on the south of the Alps it was *c.* 15·4:1·0,[23] as about Lago di Garda and Lago Maggiore. The huge morainic amphitheatres about the mouths of these valleys[24] (fig. 178), owing to the southern aspect and Mediterranean influences,[25] were the combined product of two or even three glaciations,[26] though these have been assigned to the three stages of the Würm.[27] B. Castiglioni[28] has recently published a map of the last glaciation in the Italian and adjacent Alps.

The Swiss fossiliferous interglacial beds,[29] e.g. between the Rhine and Salzach, are much smaller and rarer than in the region of the Scandinavian ice-sheet (see below). The interglacial localities are mainly in the Swiss Plain and in terraces above the valley floor within the Riss boundaries—few

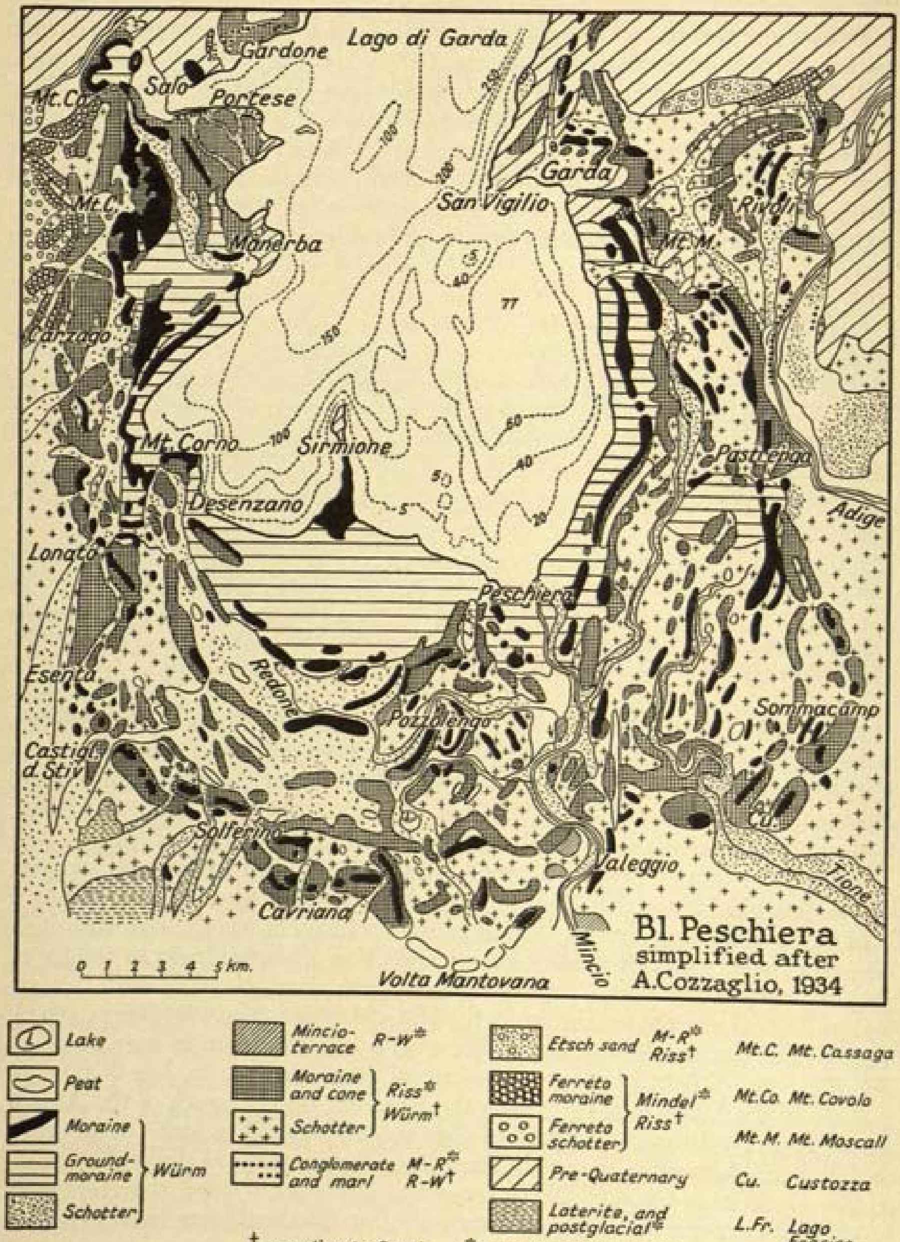

FIG. 178.—Drifts about the southern end of Lago di Garda. E. M. Todtmann, *M. Gg. G. Hamb.* 49, 1950, p. 190, fig. 1.

are found within the Alpine valleys. The beds consist of peats, gyttjas and occasionally of tufas, i.e. they were formed in general in peat moors, swamps and backwaters of streams. The *Schieferkohle* (so-called because the hard peats split when dry), which was exploited during both the world wars, consists of 120 phanerogams and pteridophytes, with 60 species of moss and other species of algae, fungi and diatoms. The plants have been frequently listed and monographed.[30] The flora resembles the present flora of Switzerland with the addition of a few plants, e.g. *Picea omorica, Ostrya carpinifolia* and *Brasenia purpurea*, which no longer live there. Switzerland was a forested land characterised by conifers, viz. *Picea alba* and *Pinus sylvestris* with *Abies* and *Alnus* dominant at optimum, though no locality gives a full interglacial sequence, possibly because the climate was too dry or too raw. The climate, with its warm summers and cold winters, corresponded to that of south-west Poland to-day. The associated animal life, viz. molluscs, also prove a more continental climate.

For O. Heer (1865) and A. Escher (see p. 898) who believed in partition there was only one interglacial age for these beds. Later workers have found

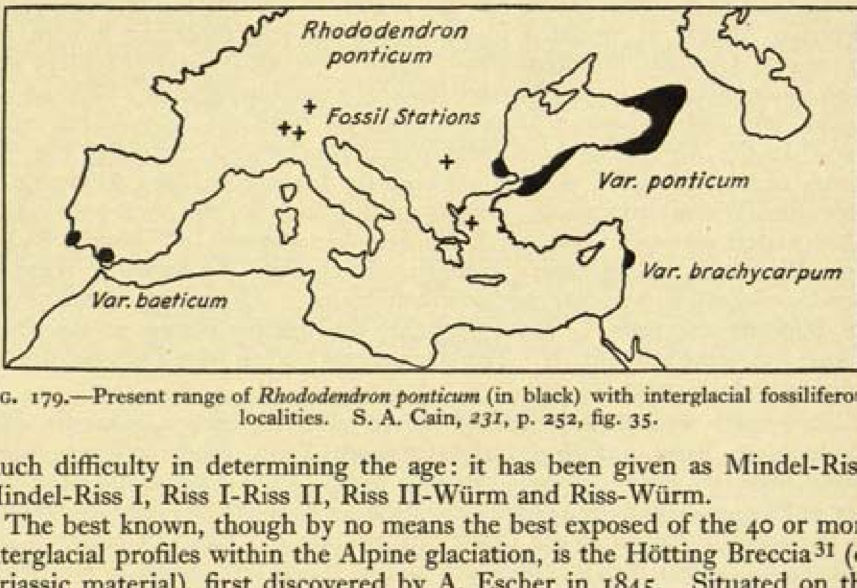

FIG. 179.—Present range of *Rhododendron ponticum* (in black) with interglacial fossiliferous localities. S. A. Cain, *231*, p. 252, fig. 35.

much difficulty in determining the age: it has been given as Mindel-Riss, Mindel-Riss I, Riss I-Riss II, Riss II-Würm and Riss-Würm.

The best known, though by no means the best exposed of the 40 or more interglacial profiles within the Alpine glaciation, is the Hötting Breccia[31] (of Triassic material), first discovered by A. Escher in 1845. Situated on the left bank of the Inn in a sheltered angle between the altitudes of 580 m and 1950, i.e. about 600–700 m higher than the other Swiss interglacial horizons and 1200 m below the present treeline,[32] it is the largest of the slope breccias and one of the very rare interglacial localities within the inner Alpine zone. It partakes in its upper part of the character of a scree, in its lower part of a cone, and is *c.* 80 m thick and almost 7 km long, having a mass possibly of 1 cu. km[33] (cf. photo[34]). Earth-movements may have been partly responsible for its formation.[35] Among the 41 species of the Hötting flora[36] (four are extinct), found in the yellowish-white calcareous muds, are *Buxus sempervirens*, the box, and most plentifully and well preserved, *Rhododendron ponticum*, the pontic rose. The latter, also entombed in interglacial lake-deposits (with varves) at Pianico-Sellere[37] on Lago d'Iseo and at Schaffhausen[38] as well as in the Balkans[39] (fig. 179), implies a mean annual

temperature[40] of 2·0° or 3·0°C higher than the locality has to-day and a snowline 400–500 m higher since it is now foreign to the Alps and grows wild in south-west Spain, Balkans, north Asia Minor and Caucasus.[41]

The interglacial age of the breccia is denied[42] on the grounds that it is preglacial, that ice and vegetation were in contact, or that the pontic rose and box, susceptible rather to dryness than to cold, are not warmth-loving but oceanic species. Yet the pontic rose in the Caucasus is one of the plants most sensitive to frost and never ascends to subalpine heights. At Innsbruck and Hötting (600 m lower than the interglacial site) it can only be cultivated to-day when artificially sheltered[43] (pl XXV A & B, facing p. 912).

Excavations and adits, which have revealed the underlying moraine,[44] the oldest moraine known from the interior of the Alps—probable occurrences of this moraine are known from several other places in the Inn valley[45]—have now removed all reasonable doubt of the breccia's interglacial position. Nevertheless, its precise age remains uncertain. O. Ampferer[46] referred it to the interglacial of the Inn valley terrace. Penck,[47] supported by others,[48] separated the two by a glacial epoch and placed it with all the Swiss interglacial beds in the Riss-Würm epoch. Later, in revising the breccias of the Bavarian Alps,[49] he reverted to an earlier opinion, replacing it with the lignites of Uznach, Dürnten (near Zürich), Wetzikon, and the clays and breccias of Pianico, in the Mindel-Riss or great interglacial. The nature of the flora (*Rhododendron ponticum* is absent from the Riss-Würm interglacial in the Alps) and the stratigraphical relationship, including the discovery of the "Sockel" moraine between the breccias and the terraces of a later (Riss-Würm) interglacial, were the justification for this view with which other writers agree.[50] The age of the *Schieferkohlenzeit* (of Uznach, Dürnten, Wetzikon, Mörschwil, Wangen, Buchberg, Kaltbrunn, Winden, Gondiswil-Zell) is, however, not definitely known. Only three of the plants are Pliocene survivals.[51] Most probably the lignites belong to the Riss-Würm but some are older.[52] The Alpine interglacials have been named the Hötting and Dürnten.[53]

The greater warmth is confirmed by the silver fir, spruce, Scots fir, oak, maple, birch, hazel, and *Brasenia purpurea* and *Trapa natans* in Swiss interglacial beds, by sweet chestnut and vine south of the Alps, and by the fact that at Pianico-Sellere (see above) 28 of the 33 floral species now live chiefly on the eastern margin of the Black Sea, and some of the rest occur in the Balkans or central Italy. Bones are rare in Swiss interglacial deposits but at Dürnten belong to *Elephas antiquus*, *Diceros merckii* and *Ursus spelaeus*. The plants of the lignites of Tyrol, Steiermark and Kärnten and of the tufas of Neustift and other Austrian localities are referred to the Riss-Würm interglacial.[54]

Suggested modifications. Heim[55] adopted Penck's classification with an important modification which Penck accepted. He correlated the middle Terrassenschotter, noticed by R. Frei, A. Gutzwiller, G. Steinmann and J. J. Tschudi, with the Riss glaciation. The Hochterrassenschotter (P. Beck's Rinnenschotter[56] in part), whose glacial age had never been rigorously proved, he relegated, following F. Mühlberg,[57] to the Mindel-Riss; it contains lignite and hippopotamus and a member of the salmon family[58] and a molluscan fauna which, like the attendant pollen, points to a rich vegetation.[59] It is sandwiched between moraines over wide areas (as seen in many sections)

and as far as the mouths of the Alpine valleys, and was built up, not by overloaded glacier-streams, but by a lessening of the gradient (see p. 446).

The Penck-Brückner succession, in either its original or its modified form, has been challenged,[60] especially by those who disclaim the glacial age of the schotter (see p. 446). The Günz in particular has been doubted or rejected[61]; for as Penck[62] confessed, no Günz-Mindel horizon is yet known, and a Swiss specimen of *Elephas meridionalis* or *Machairodus latidens* has yet to be found.[63] There is no loess of Günz age[64]—this argument is inconclusive since the Mindel also lacks a loess (see p. 1027). The downward erosion between the two Deckenschotters, almost the sole foundation for the earliest glaciation, may be interstadial only[65] or of tectonic origin.[66] Other glacialists assail both Günz and Mindel glaciations[67] since only two glaciations are demonstrable in many places, e.g. the Eastern Alps, Swabia, west Switzerland and the French and Italian Alps. A Günz or early Pleistocene age has been given to an ancient solifluxion in France[68] and in the Low Countries.[69]

On the other hand, it is contended that to the classic four should be added a fifth glaciation which either preceded them as at Basle[70] (this Sundgau schotter is regarded as upper Pliocene[71]) and in Bavaria—Eberl's "Donau glaciation"[72] (divided into 1, 2, 3) which is otherwise unknown, though it has recently been claimed for the southern Alps[73] and four pre-Günz schotters and Donau loess have been maintained for south-west Germany[74]—or was sandwiched between the Riss and Würm.[75] This extra glaciation has been variously termed the Mühlbergian,[76] Kander[77] or Néorissian[78]; F. Mühlberg[79] correlated it with Steinmann's Middle Terrace of the Rhine (see p. 1042). Recent work,[80] e.g. in the Aare and Linth, but unconfirmed elsewhere, has (on the strength of moraines in schotter) inserted between the Mindel and Riss glaciations two middle glaciations, the Kander and Glütsch (Thun), which were associated with the Rinnenschotter and may be merely advance phases of the Riss glaciation.[81] They either replaced the Günz and Mindel or followed the great interglacial epoch of the Hochterrassenschotter and the excavation of the Alpine valleys. The warm Schieferkohle interglacial parted them from the Riss glaciation.[82] The absence of interstadial deposits in some larger valleys has been connected with the persistence of their glaciers while the glaciers in smaller valleys disappeared.[83]

Recent investigations[84] between the Lech and Isar, e.g. in the Rhine, Aare and Iller-Lech and along the northern fringe of the Alps, have also tended to show that the glaciations which preceded the Würm were each double or treble and that the Würm itself was two- or three-phased. For example, the Lower Terrace is double[85] in the Eastern Alps, in the Rhine between Basle and Schaffhausen, and in the vicinity of Köln (see p. 1042). A threefold division is claimed[86] for the Zürich See area of Switzerland (J. Hug), for Bavaria (K. Troll), for the Upper Rhine (D. Kimball and F. E. Zeuner) and for Upper Swabia (B. Eberl, cf. p. 1161). Nevertheless, Penck[87] holds that the moraines upon which Eberl and others base their *Vollgliederung* have not been proved to be other than stadial features.

W. Kilian's *Néowürmian*[88]—B. Aeberhardt's *néoglaciaire*[89] and O. Ampferer's *Schlusseiszeit*[90] (Schlern, with Gschnitz and Daun as retreat stages[91]) —is seemingly not a true glaciation[92] (as Ampferer himself admitted in 1947), though it followed an interstadial oscillation which has been equated with the Alleröd oscillation[93] (see p. 1431) and has found occasional support on field evidence,[94] as in the Oberengadin, from pollen analyses[95] of interstadial

deposits, and theoretical considerations based on Milankovitch's curve.[96] It had possible equivalents in the Eastern Alps[97] and other Alpine regions[98] and in the Pyrenees.[99] Nevertheless, it was not preceded by a period of any appreciable warmth or length—the Climatic Optimum followed it—and therefore was not a true glaciation.[100] If any period deserves the name it would rather be the "Little Ice Age" of Matthes (cf. p. 1496). The Bühl stage (see ch. XLII) has been raised to the dignity of a glaciation[101] and correlated with the Baltic moraines of north Germany.

Departures from Penck's original scheme or *Grundgliederung* appear, therefore, to be mainly three; first, either the possible elimination of the Günz glaciation (leaving three glaciations definitely established) or the insertion of a still earlier Donau (Danube) glaciation; secondly, the double or triple nature of each glaciation—the Kander and Glütsch may be two such phases—according to the *Vollgliederung*; and thirdly, the relegation of the Hochterrassenschotter, the pivot of all later classifications and nomenclatures, to the Mindel-Riss interglacial and its replacement by the middle terrace which corresponds to a fourth glaciation or a short advance intruded into the Riss-Mindel interglacial.

The Carpathians have not yet produced any stratigraphical evidence of interglacial epochs[102] (cf. p. 921).

2. *Pyrenees*

The Pyrenean valleys have four well-defined terraces which since Penck[103] described them have been linked with the classic Alpine four in almost every conceivable way. This is set out in the following table for the Garonne:

	Obermaier[104]	*Penck*[105]	*Wiegers*[106]	*Bayer*[107]
First Terrace (150 m)	Günz	Pliocene	Günz	Pliocene
Second Terrace (100 m)	Mindel	Günz		
Third Terrace (55 m)	Riss	Mindel	Mindel	Mindel
Fourth Terrace (15 m)	Würm	Riss	Riss	Riss
"Alluvium"	—	Würm	Würm	Würm

The first terrace is probably Pliocene.[108] How the other terraces should be correlated is still undecided though the occurrence of mammoth in the so-called Alluvium makes its reference to the last glaciation (Würm) very likely. No supporting evidence in the shape of interglacial deposits has yet been found.[109] Penck's correlation seems the most probable.

3. *Belgium*

The Quaternary deposits of Belgium[110] are classified by the Belgium Geological Survey[111] as follows: Moséen, Q1, Campignien, Q2, Hesbayen, Q3 and Flandrien, Q4. Sections showing the full succession occur at Spiennes near Mons and at Hofstade near Malines.[112]

The Moséen of M. Mourlon[113] consists of marine (= *crue moséene* of A. Rutot[114]) or fluviatile sands[115] with occasional remains of *Elephas trogontherii*, *Diceros leptorhinus*, *Dicerorhinus etruscus* and *Hippopotamus* and *Corbicula fluminalis* at the base and traces of vegetation, e.g. tree trunks, branches and fruits, and terrestrial molluscs and eoliths[116] (= reutelien, mafflien, mesvinien). The age is Pliocene or early Pleistocene.

The Campignien forms current-bedded sands and gravels in the lower parts of the valleys with a mixed fauna in the valley of the Scheldt, including the cold forms (mammoth, woolly rhinoceros, Irish deer and reindeer) and hyaena and lion, that continues into the Hesbayen and Flandrien practically unaltered.[117] The industry is Strépyian, Chellean and Acheulian and the age Riss glaciation.[118]

The Hesbayen (= Brabantien of A. Rutot[119]), the equivalent of the upper ergeron of the Somme,[120] was deposited in the Riss-Würm interglacial epoch[121] and contains Micoquean and Aurignacian.

The Flandrian (= *Zanddiluvium* of H. C. Staring[122]), which covers one-third of the country, including much of the north-west, consists of marine sands with continental beds and peats west of the lower Rhine terraces. While a marine origin is affirmed,[123] this is denied by those who believe they are fluviatile[124] since the marine shells occur only near the coast and the beds contain fluviatile shells and peats.

The *Limons supérieurs* or *ergerons*, which may have been nivéo-fluvial,[125] belong to the last glaciation.

4. *North Germany, Holland and Denmark*

Number of glaciations. In the north German succession, which has been well summarised,[126] a lower and an upper *Diluvium* have long been recognised, both stratigraphically and faunistically (see p. 898), irrespective of the divergent views which have been entertained as to their origin. A two-fold glaciation, first perhaps really established by Helland in 1879,[127] was later frequently advocated.[128] It was based upon the two *Diluvium* horizons, the transport of boulders[129] (see below), and the double system of striae in north Germany, Scania and Bornholm (see p. 898), the products of a Meridional Ice-stream[130] proceeding generally from north to south and of a movement from east to west or even north-west, as in Scania. It was corroborated by the Rixdorf bore as German geologists, especially W. Dames, recognised in the 80's of last century—the first interglacial was the *Paludina* horizon, the second, the Rixdorf horizon—by observations in the Hamburg area[131] and for the region between Halle and Weissenfels.[132]

The various drifts in north Germany have been correlated among themselves by the Danish numerical method,[133] by the heavy minerals[134]—in north Germany, the Weichsel has relatively much garnet and zircon with amphibole, corundum and apatite, the Elster glaciation epidote and clino-zoisite, and the Saale and Warthe a mixture of all these minerals—and by the orientation of the boulders,[135] for during the Elster glaciation the direction was from the north-east, during the Saale from the north and north-west and during the last glaciation from the north-north-west (figs. 180, 181). It is also ascertained from the percentages of boulders of different kinds of rock[136] of which 190 have been so used (some workers are unable to make this differentiation[137] or emphasise the role of nudging and variations in the direction of flow within one glaciation[138]). Thus Cenomanian erratics are more numerous in the latest drift[139]; the percentage of erratics from various parts of Baltoscandia varies in the Dutch and Danish drifts[140]; the Elster glaciation in Germany is distinguished by east Fennoscandian (60%) and the Saale glaciation by west Fennoscandian material[141] (40–70%), and by a high percentage of Baltic quartz-porphyry,[142] though the latter has been associated

with the Warthe glaciation.[143] The Elster drift in lower Saxony and in Sylt has a high component of Oslo material.[144] Hesemann calculated the percentages of the boulders from east Fennoscandia, central Sweden, south Sweden and Norway respectively and expressed them as whole numbers: the Elster gave a figure of about 6310, the Saale figures such as 2170, 2260 or 1180 and the Warthe 4330 or 3340. East of the Oder these methods fail: they would require a subdivision of the east Scandinavian contingent.[145]

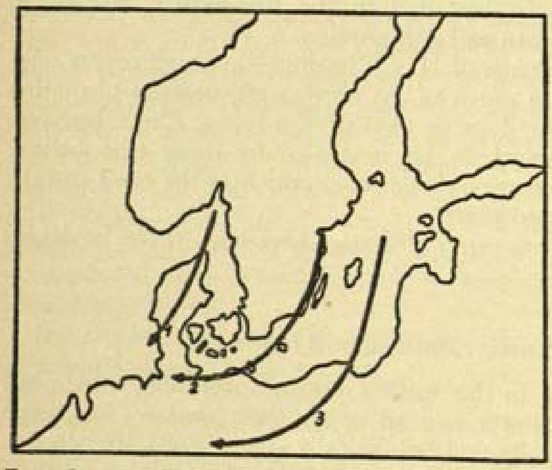

FIG. 180.—Main flow-lines during the Elster glaciation. 1, Norwegian; 2, south Swedish; 3, east Fennoscandian. P. Woldstedt, *1822*, p. 314, fig. 65.

Penck's three glaciations,[146] postulated for north Germany and Denmark on stratigraphical and palaeontological grounds, are almost universally admitted[147]: Keilhack[148] (1927) designated them *Elster*, *Saale* and *Weichsel* (in alphabetical and chronological order)—the intervening interglacials have been named *Bel*, *Es*, *Saw* and *Waw* (see p. 953). They have been established by the two interbedded interglacial horizons found in one and the same bore in a number of north German localities[149] (e.g. Phoeben, Tempelhof), and in sections in the islands of Sylt[150] and Föhr[151] and along the Kiel Canal.[152] According to H. Menzel, the penultimate interglacial contained *Paludina diluviana*, *Dreissenia polymorpha*, *Pisidium amnicum* and *Planorbis micromphalus*, and the last interglacial *Paludina duboisi*, *Zonates acieformis* and *Helix tonnensis*. The interglacial horizons have their counterpart in the interglacial river-terraces, with "warm" molluscs and animals, which line the valleys that fall northwards from the German Mittelgebirge.[153]

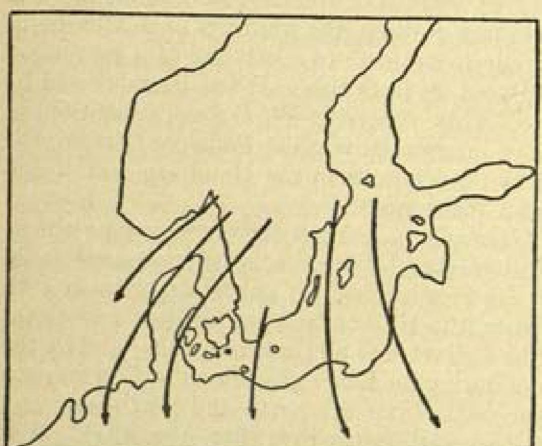

FIG. 181.—Main flow-lines during the Saale glaciation. P. Woldstedt, *1822*, p. 315, fig. 66.

Denmark also had three glacial horizons. The oldest forms the deposits below the Yoldia clays of Esbjerg (see p. 953) and the clays with *Tellina* in Rögen Klint. To the second glaciation belong the clays of the Bakke-Öer (p. 944). A freshwater interglacial horizon (probably

belonging to the earlier interglacial), with diatoms and other forms, has been found on the floor of the North Sea,[154] e.g. off Wangeroog (see p. 1363).

A fourfold classification of the German and Danish drifts, influenced by Alpine research, has been frequently advocated,[155] either from morphological studies or from interglacial sequences. This has been done by adding an earlier "Elbe"[156] or "Baltic"[157] glaciation—a cold phase preceding the Elster glaciation has been recognised in the terrace-system near Warthe in Silesia[158] and three interglacial transgressions have been postulated[159] (Hamburg, Dittmarsch and Eemian). Evidence for an Elbe glaciation is seen in the deposits with Silurian pebbles (from Jämtland, Gotland and Ösel) which occur in the Baltic region,[160] e.g. near Stettin, in Poland in the oldest beds in the area between Warsaw, Piotrkow and Lodz,[161] and in Galicia (near Jaroslaw); in a cold layer at the base of a peat which underlies the Cracow (Mindel) glaciation[162]; and in the "Upper Terrace", with occasional northern erratics, about the Harz Mountains.[163] The cold fauna of the Icenian of Holland (p. 697), the early glacial horizon in the lower Rhine beneath the Tiglian, (see p. 1044), and the gravels of Süssenborn would also belong here.[164] A further indication is the occurrence of loess in banded clays of the Elster glaciation in Thuringia[165]—this glaciation itself has been equated with the Günz.[166] Alternatively a "middle Drift"[167] (Warthe glaciation, Fläming phase) has been inserted between the Saale and Weichsel glaciations, its outwash, e.g. in the Lüneburger Heide and Niederlausitz, grading into the Lower Terrace of the Weser, Aller, Leine and Elbe: Keilhack,[168] who with F. Wahnschaffe and E. Werth regards the Warthe as a second oscillation of the last glaciation (see p. 1164), strenuously denies this. Even a five-fold or six-fold glaciation has been postulated,[169] largely on the evidence of bores in the neighbourhood of Magdeburg: the two preceding the Elster are termed Alster and Elbe. As in the region of the Alpine glaciation (see p. 937), double- or triple-phased glaciations have been recognised in north Germany (see p. 919). Thus three-phased Elster and Saale glaciations have been postulated for Saxony.[170]

The number of ice-invasions of Holland has long been disputed. Three[171] or four[172] glaciations are still advocated, though most writers (together with the Dutch Geological Survey) have agreed that there was only one glaciation[173]—this *groote ijstijd* is bracketed with the Riss.[174] It is affirmed, however, that the Elster ice crossed the lower Rhine.[175] Fine sands with Scandinavian erratics occur below the till in Holland and Scandinavian ice therefore was not far distant—this ice may have belonged to a separate glaciation (H. v. Capelle, J. Lorié) or an oscillation of the ice which laid down the boulder-clay[176] (J. F. Stenhuis, P. Tesch). The marine sands (unbottomed) at the base of the Pleistocene have been equated with the Günz[177] though they belong to the Mindel-Riss.[178] It would seem that there were two glaciations[179]; for the Hondsrug, as proved by stone-counts, has a core of Elster drift with 50–60% of east Fennoscandian crystalline erratics[180]; and pollen diagrams prove two interglacials in the north-east[181] and a complete succession from Günz to Riss, including a Mindel-Riss flora. Blocks, enclosed in the typical till in the northern and north-eastern parts of the Netherlands, show remarkable quantitative differences in the sedimentary and crystalline erratics, in mineral content, and—in addition to those caused by weathering—in the colour of the boulder-clay.[182] During the Saale

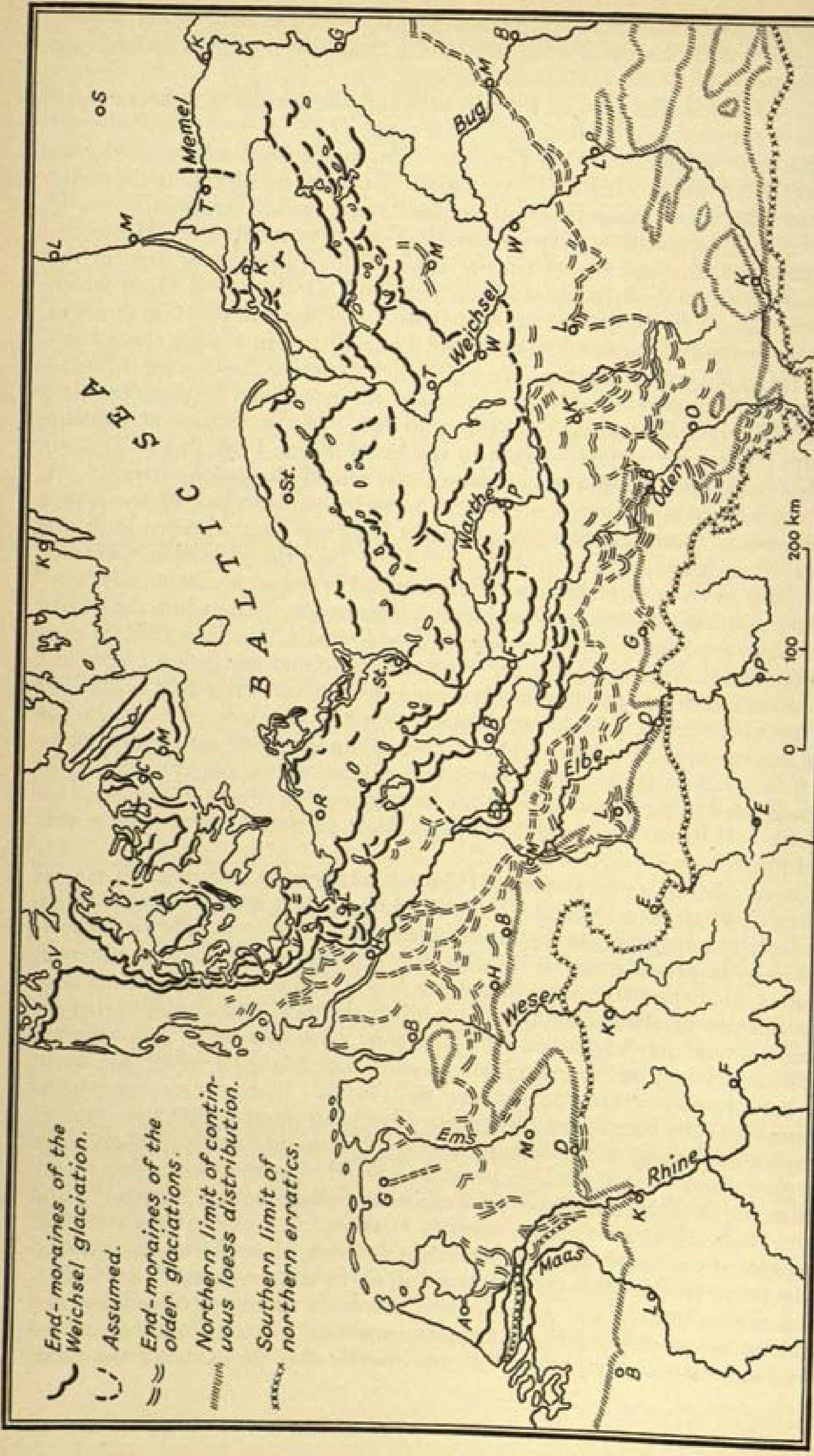

FIG. 182.—Map of the most important end-moraine lines of north Germany, of the southern limit of northern erratics, and of the northern limit of continuous loess. P. Woldstedt, *1822*, p. 31, fig. 4.

glaciation the junction between the North Sea and the Baltic ice lay in the Lüneburger Heide.[183]

The four cold phases have been named in Holland,[184] Praetiglian, Taxandrian (previously termed Brabantian), Drenthian and Tubantian, and the interglacial epochs, Tiglian, Needian and Eemian. The Praetiglian has *Elephas planifrons*, the Tiglian *E. meridionalis*, the Needian *E. antiquus*, and the Drenthian and Tubantian *E. primigenius*. The Tiglian's most conspicuous mollusc is *Vivipara glacialis*, that of the Needian *V. diluviana*.

Limits of glaciations. While the outer limit of the drift is fairly easily ascertained, the bounds of the various glaciations within it are much more difficult to draw and are still to be accurately determined. They were sought later in Holland and north Germany than in Switzerland and North America, and even to-day opinions conflict about them as well as about their number. At an early stage, the ice followed the Baltic depression[185] as a vast Older Baltic Ice-stream[186] or Palaeobaltic Glacier[187] of uncertain extent; the lowest boulder-clay at Hamburg, Rüdersdorf, Sylt and Rügen has been assigned to it.[188]

The Saale was generally the main glaciation (*Haupteiszeit*) in north Germany,[189] though the Elster drift which has been found in deep bores in the Hamburg and Bremen districts emerges from under it in numerous places[190] (fig. 182), e.g. in Westphalia, Thuringia, west Saxony and Silesia, in Poland and north of the Carpathians, and R. Grahmann[191] regards the Elster as the major glaciation. In Holland and the lower Rhine the two glaciations may have been co-extensive[192] though the ice only crossed the Rhine in Saale time[193] (cf. above).

The Weichsel boundary has occasioned much controversy. Klockmann,[194] who remarked that lakes are confined to the Upper Diluvium and loess to the Lower Diluvium, placed it east of the Elbe or generally along this valley and that of the Baruth. Later writers,[195] including K. Keilhack and the majority of north German and Polish geologists, thrust it beyond the Elbe to the Fläming or Warthe line[196] and even farther south,[197] e.g. to the Lüneburger Heide, the Aller and Weser, the Breslau-Magdeburg *Urstromtal*, and the Lausitz (229 m), Trebnitz (255 m) and Katzengebirge (228 m). The Warthe line, they contend, is the outermost boundary of well-marked push moraines and outwash plains and does not conflict with the distribution of the loess. It accords well with the somewhat scanty palaeolithic evidence (see p. 1046) and with the erratic composition of the drifts, resembling more closely that of the later (Weichsel) drifts than that of the Saale glaciation but differing from both. Stone-counts,[198] based partly upon the brown Baltic porphyry (and, unlike the topographical relationships, of an objective nature) show, however, that a definite erratic line runs for over 1200 km through eastern Germany and Poland and follows none of the recognised limits but coincides roughly with the Warthe line and the northern edge of the loess between Magdeburg and Breslau: the ice must have receded before the advance to at least the Åland Islands. The limit of the brown Baltic porphyry is equated with the Warthe glaciation[199] or with the Saale glaciation.[200]

Klockmann's line, now styled the Brandenburg Line, has been revived[201] since it agrees with the distribution of the disturbed Eemian deposits[202] (see below) and of the fresh surface forms,[203] first emphasised by Penck, including the lake-landscape and the tunnel-valleys[204] (see p. 241).

It includes the most easterly and northerly interglacial deposits of the Brörup type[205] (figs. 183, 184) and all the loess localities, including the northernmost outliers[206]: lateglacial loess has been found, however, in Lithuania[207] and on Rügen.[208] On this view, the interglacial Rabutz clay, with its fauna of *Elephas antiquus*, *Diceros merckii* and *Cervus elephas*, unanimously regarded as belonging to the last interglacial, was sealed by solifluxion[209] and not by the till of the last glaciation as has been suggested,[210] and does not lie between the Saale and Warthe glaciations.[211] The lacustrine *Kieselgur* of the Lüneburger Heide,[212] though placed in the last interglacial, belongs to the penultimate interglacial: it records a periodicity in solar radiation.[213]

Woldstedt,[214] supported by Polish and other evidence,[215] believes the Warthe moraines are separated from those of the later Weichsel glaciation by an interglacial epoch (the Eemian), and from the preceding Saale glaciation by an interstadial—the podsol was of less depth in the Saale-Warthe interval. The 50 miles (80 km) of disturbed Eemian deposits give a minimum measure of the retreat (see p. 946).

The arguments seem to dispose of the view, often stated,[216] that the Baltic moraine is merely recessional and that the drifts within and without are petrologically and stratigraphically alike and have the same state of weathering.

The limit of the last glaciation, when traced westwards, departs more and more from the Mittelgebirge and from the older glacial boundaries. Its boundary in Holstein has been pushed farther west[217] as the result of studies of the morphology and stone counts, and is now clearly delineated in Jutland,[218] though confusion existed earlier because solifluxion products had been mistaken for boulder-clay.[219] Their modern reference to solifluxion[220] harmonises with the distribution of the *Bakke-Öer* ("hill-islands"), viz. mounds of older drift, of smooth outline, which range in size from "islands" 2000 sq. km in extent to small, isolated hummocks and are cut into and in part covered by the sandy outwash of the last glaciation in west Jutland.[221] The boundary also agrees with the hummocky landscape of the east,[222] with the interglacial basins (see p. 948), and with the erratic constituents of the drift[223] (basalt erratics, restricted to the upper drift, occur 10–15 km farther west and give the maximum extent of the ice over a stretch of *c.* 100 km). The Warthe moraine can be followed to Hamburg and the region about the Eider[224] but is not traceable with any certainty farther north. Danish geologists extend this glaciation to the west coast, and others suggest either that its boundary merges into the belt of young end-moraines in Jutland[225] or, like the other ice-fronts, runs across the floor of the North Sea[226] (see fig. 256, p. 1229).

To correlate the last glacial limit with either the Brandenburg or the Warthe line is clearly inconsistent with an extension of this ice into Holland demanded by some geologists.[227]

Eemian and Holstein seas. The Eemian beds, which play no morphological role, are generally grey or greenish-grey clays or coarse and fine sands, 1–40 m thick in Holland and 3–14 m thick in the Eem valley itself in the province of Utrecht. Frequently disturbed and imbricated by subsequent ice-pressure, they range widely south of the Baltic,[228] either *in situ* or, e.g. in Schleswig-Holstein, as enclosed masses in the drift. They extend eastwards from Terschelling and Texel and the Belgian coast (shells of *Tapes senescens*[229] have been detached from submarine outcrops of the Eemian near the Dutch

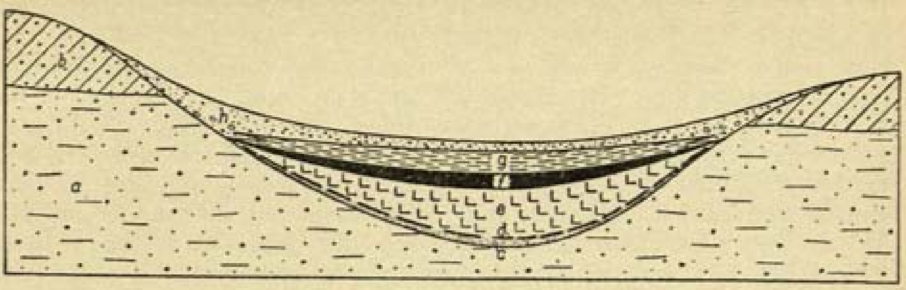

FIG. 183.—Diagrammatic section of an interglacial basin of Brörup type. *a*, sand and gravel; *b*, boulder-clay; *c*, lower basin sand and clay (*Beckensand*); *d*, lower peat; *e*, freshwater marl or kieselgur; *f*, upper peat; *g*, upper basin sand; *h*, covering boulders and sand (*Geschiebedecksand*). P. Woldstedt, *E. & G.* 1, 1951, p. 84, fig. 1.

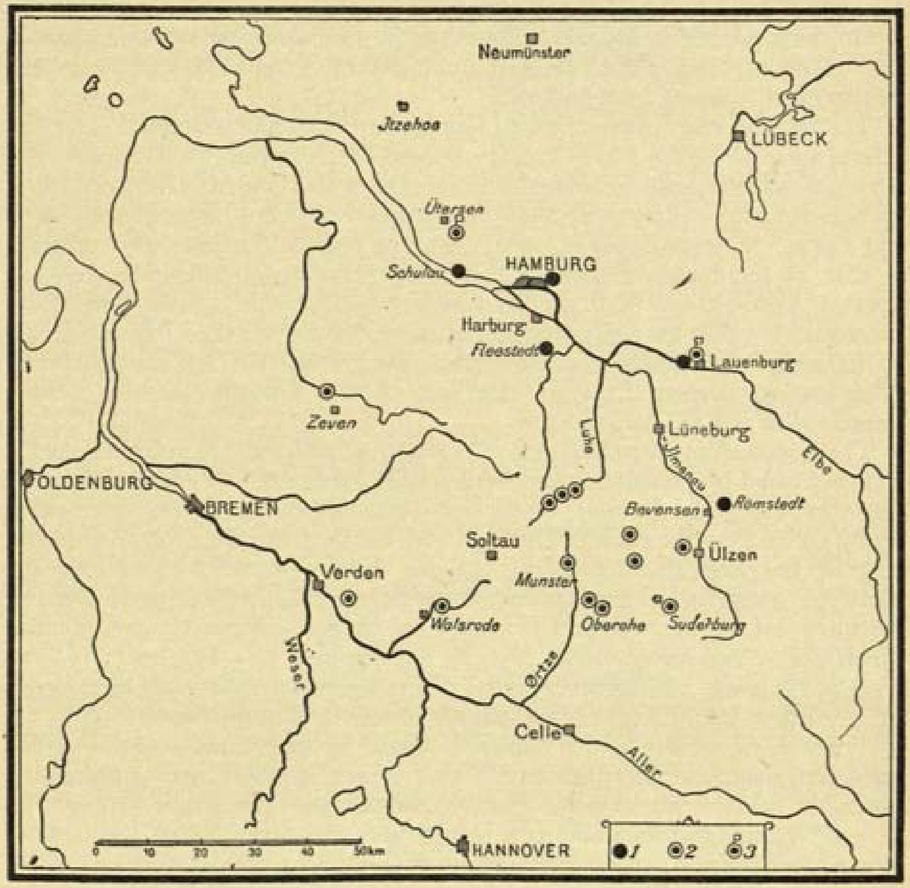

FIG. 184.—Distribution of the Brörup interglacial type in north-west Germany: 1, last interglacial; 2, penultimate interglacial; 3, freshwater deposits caused by marine sediments of penultimate interglacial. K. Jessen & V. Milthers, 854, p. 311, fig. 30.

frontier and from the Zuider Zee (−25 m), Amsterdam and the Eem valley): J. Lorié[230] has listed the Dutch and O. Grahle[231] the north-west German occurrences, and J. F. Stenhuis, E. Dittmer, K. Gripp and P. Tesch have constructed maps of the Eemian shore.[232] The beds occur too in the Frisian Islands, e.g. Sylt—the *Tapes* shells are washed up to-day in relatively large numbers on these islands—and, under a stretch of 55 km in south-west Jutland and north-west Schleswig,[233] beneath Holstein,[234] along the line of the Kiel Canal,[235] in the Danish islands, Rügen, the whole of West Prussia and East Prussia, near Thorn in Posen and in Estonia and the Dwina region.[236] The Eemian included the celebrated Elbing Yoldia Clay[237] which A. Jentzsch described in 1876 and later years and which contains plants, molluscs, foraminifera, radiolaria and diatoms. *Tellina calcarea* clay at Odsherred and marine shells in the moraines of north-east Sjaelland demonstrate that the Eemian Sea invaded the Kattegat.[238] It probably extended far northwards towards Scania.[239]

Many transported masses have been discovered in east Germany where A. Jentzsch[240] first detected them, as well as in Sjaelland, Fyn, and over a breadth of 50 miles (80 km) in Jutland.[241]

On the west, the Eemian is represented by the sands, gravels and clays of the Flandrian Sea which covered one-third of Belgium from the North Sea to north-west of Maastricht.[242]

The Eemian clays, discovered by Forchhammer[243] and described as Yoldia Clays, were called Cyprina Clays by Berendt[244] from their constituent shell *Cyprina islandica* and to avoid confusion with the lateglacial Yoldia Clays of Scandinavia. They were later (1908) named Eemian[245] since *Cyprina* is not a principal fossil of the horizon, unless perhaps in the east, and the fauna is that of the Dutch Eemian.[246] The name is derived from a common species, *Tapes aureus* Gm. var. *eemiensis* Nordm.[247] or a variety of *Tapes senescens*.[248] It is the only extinct species in a fauna[249] which, generally rich in individuals, includes 120 molluscan species and the following: *Yoldia* (*Portlandica*) *arctica*, *Cyprina islandica*, *Astarte borealis*, diatoms, *Phoca groenlandica* and *Gadus polaris*.

The Eemian Sea resembled generally the present North Sea in its salinity,[250] as is indicated by its diatoms and the size of its molluscs. Its temperature,[251] however, except in that part of the sea which was characterised by *Yoldia*, was warmer than the present Kattegat and North Sea and approached rather that of the English Channel or the sea farther south. The fauna, for example, comprised several species which now live in the Mediterranean and off the coast of Portugal and France,[252] such as *Haminea navicula*, *Lucina divaricata*, *Syndesmya ovata*, *Mytilus* cf. *minimus*, *M. lineatus*, *Gastrana fragilis*, *Eulimella nitidissima*, some of them unknown in north-west Europe in any other interglacial or postglacial horizon. The molluscs include no truly northern shell (*Cyprina islandica*, judged by its present range,[253] is not northern), and of the diatoms,[254] 57·7% are southern and only 4·1% northern. The warm oceanic climate[255] agrees with the higher temperature of 2·0°C considered reasonable for Denmark at this time,[256] with the absence of erratics from the clays or any sign of drift-ice,[257] and with pollen analyses of the deposits.[258] The upper part of the succession however is characterised by fewer Lusitanian forms and by the appearance of a number of boreal species, especially among the gastropods.[259]

That this marine incursion of wide areas bordering the Baltic and the North

Sea (fig. 185)—Kirmington in Lincolnshire and March and Kelsey in Holderness may belong here (see p. 1007)—was only shallow[260] is demonstrated by the molluscs and diatoms. Its shore, for example, was not far from the present Baltic coast near Kiel.[261] The sea gradually (rapidly ?[262]) invaded the land, its clays replacing sands and gravels and its marine beds the underlying freshwater strata[263] which contain *Paludina diluviana*, *Lithoglyphus naticoides*, *Valvata naticina*, *Corbicula fluminalis*, *Dreissenia polymorpha*, *Pisidium obtusale* and *Unio*. It also submerged the land vegetation which, as in Holland and between Esbjerg and Kolding in Jutland and at Clacton-on-Sea in England, was in its optimum phase of mixed oak forest.[264] In Holland, where the Eemian flora was first discovered in 1930,[265] this forest was both preceded and followed by a coniferous period.[266]

Indications in north Friesland suggest there may have been two invasions.[267]

According to Penck,[268] the warm Eemian of south Jutland and Holland was contemporaneous with the arctic fauna of the Portlandia stage of north Denmark at Skaerumhede (see below), East Prussia, Gulf of Riga and Finland (between Gulf of Finland and Lake Ladoga), near Leningrad, Lake Onega and the Dwina—here the sea reached *c.* 80 m above present sea-level.[269] A strait between the Arctic Ocean and the Baltic admitted a cold current from the north while a warm current entered the Baltic from the North Sea.[270] On its coast grew *Carpinus*, *Quercus* and *Ulmus*. The Portlandia Sea may have been the late-interglacial phase of the warm interglacial Eemian: pollen analyses confirm this succession.[271] The diatoms suggest that the Holstein Sea (see below) was colder than the Eemian Sea though the temperature conditions varied locally and make comparisons difficult.[272] The *Portlandica arctica* in the drifts of Latvia (see fig. 187, p. 954) were derived from an interglacial sea over the southern half of the Gulf of Riga.

FIG. 185.—Map of the Eemian Sea. F. J. Faber, 477, p. 395, fig. 123.

The age of the Eemian has been much discussed since Forchhammer[273] first placed it in the Pleistocene. While some,[274] including the monoglacialists, put it in the preglacial, a reference incompatible[275] with its lack, generally speaking, of preglacial species and with the abundance and variety of mineral grains which are diagnostic of the Pleistocene, most assign it to an interglacial epoch,[276] either the first[277] or the second,[278] or in the case of those who accept four glaciations, to the middle interglacial[279] or the Warthe-Weichsel interglacial.[280] Others make its age differ in east and west[281] or deem it to be preglacial in East Prussia, first interglacial in the lower Vistula, and second interglacial in west Germany and Schleswig.[282]

It seems probable, however, that there were transgressions in both the first and second epochs,[283] Penck's Holstein and Eemian seas,[284] which with the Icenian gives Holland three Pleistocene transgressions.[285] K. Gripp[286] has suggested the name Stör Sea for the Holstein Sea (to avoid confusion with the lower Miocene Holstein horizon). This sea, whose distribution and fossil content (over 50 molluscan species) in Schleswig-Holstein and Germany have been fully described,[287] extended in a big bay up the Elbe,[288] where marine clays lie between freshwater sands and clays and peats, and into Holland[289] where palynology proves a climate like that postulated for Jutland and north-west Germany. H. Neumann,[290] because of slight differences in the faunas but on no other stratigraphical evidence, has referred the deposits of the Holstein Sea to two transgressions, an earlier Hamburg Sea and a later, Dittmarsch Sea, of Elster-Saale and Saale-Warthe age respectively: the distinction between these seas is, however, not recognised.[291]

While the wide connexion over the Kattegat and Skagerrak must have ensured similar conditions, e.g. in respect to salinity, in both the east and the west and during successive invasions, it has been doubted whether the same total fauna would in fact return a second time. Thus three horizons in Denmark, each of them named Yoldia Clay, viz. the Esbjerg Yoldia Clay of the first interglacial, the Older Yoldia Clay at Vendsyssel and Skaerumhede of the second interglacial, and the lateglacial Yoldia Clay in Vendsyssel, while generally similar, have significant faunal differences[292] (see p. 1025).

Recent evidence seems to sustain the correlation of the Eemian proper with the second interglacial, at least in west Europe. The Dutch Eemian lies definitely above the Saale drift[293] and below the Rhine *Niederterrasse* (Dutch: *Laagterras*). Between Jutland and the Zuider Zee, the Eemian has no morainic cover[294]—it thins out against the older boulder-clay of the Bakke-Öer (see p. 944)—while in the eastern strip of Schleswig-Holstein and Jutland bores prove that it was buried by thick drifts of the last glaciation and was disturbed by the advance of the last ice-sheet[295]—it overlies the Warthe drift.[296] The Skaerumhede bore (see below) shows that it belongs to the upper part (*Portlandia arctica* zone) of the Skaerumhede series.

Yet on the Kiel Canal, as bores and dredgings establish, and at Graudenz and Marienburg in the lower Vistula basin, the Eemian seems to be overlain by an older drift. In Ristinge Klint, it may also be in an earlier interglacial.

In south Holstein, the deposits which resemble the Eemian but lack its Lusitanian warm element and its characteristic extinct shell, overlie the Lauenburg Clay.[297] This clay, up to 70 m or 100 m thick, is black or greenish-grey in colour and rich in foraminifera and becomes sandy when traced up the valleys. It has a wide distribution in north-west Germany, extending from Hamburg to Groningen in Holland and occasionally appears at the surface or at exceptional altitudes as the result of later ice-pressure. It is sandwiched between two boulder-clays about Hamburg and Lauenburg and belongs to the first interglacial epoch.[298]

Terrestrial deposits. Interglacial freshwater beds, found as basin infillings (marls, Kieselgur and peats) or as thin streaks in secondary, distributed positions in the drifts, consist of littoral and bottom muds (calcareous, ochreous, diatomaceous). They range extensively through north-west Europe,[299] from Hamburg to Berlin, East Prussia and Poland (Chelmo), and westwards into Holland and Denmark—the description of the interglacial

localities in north Germany occupies 40 pages in Wahnschaffe-Schucht's book[300] (1921). The associated flora reveals the change of climate from cool to warm and back again to cool.[301] Most of the north German interglacial localities belong to the Saale-Weichsel interglacial since the Elster-Saale interglacial deposits are far more deeply buried and are accessible for the most part only in bores.[302]

The molluscan fauna[303] contains *Valvata naticina*, *V. piscinalis*, *Lithoglyphus pyramidatus*, *Neritina serratiliniformis* and *Pisidium asteroides*, together with *Vivipara* (*Paludina*) *diluviana* Kunth[304] whose precise relation to the modern species *V. fasciata* Mill (which inhabits tributaries of the Black Sea) is in dispute. While Neumayr[305] and some later palaeontologists[306] regard them as identical or forming a *Formenkreis*, many have deemed the Pleistocene form to be specifically distinct.[307] It is also referred[308] to *V. pyramidalis* or *V. atra* of Italy (these forms differ only in their colour) or is said to be identical[309] with *V. clactonensis* S. V. Wood.

E. Keilhack's suspicion[310] that the *Paludina* horizon was interglacial was confirmed by the discovery of an underlying boulder-clay at Rüdersdorf[311] and later at other localities in the Berlin area[312] and by pollen analyses[313]—it coincided with the mixed oak forest. Nevertheless, while the interglacial age is now established, its age is still somewhat uncertain: it is referred to the second or Rixdorf interglacial[314] or to the first or Elster-Saale interglacial[315] since its associated forest flora contains *Abies* which in the Berlin district is only found on this horizon.[316] It is, however, probable that the Rixdorf horizon is one interglacial younger than the Paludina zone[317] or belongs even to the Warthe-Weichsel stage[318] or Weichsel interstadial[319] since it contains a mixed fauna of cold and temperate plants. In the Netherlands,[320] the *Paludina* horizon may belong to an interglacial epoch earlier than in the east, e.g. in Berlin, though the occurrence of *Azolla filiculoides* in both areas suggests the beds are of the same age.[321] Two *Paludina* horizons have been claimed for Mark Brandenburg.[322]

Of interglacial age also are the terraces which occur in the valleys north of the Mittelgebirge, e.g. the classical area between Halle and Weissenfels and the Middle Terrace north of the Harz Mountains which lies in the Elster-Saale interglacial, and the tufas at the edge of these mountains[323]—the fauna has warm gastropods and remains of *Diceros merckii*.

The Mauer sands, found in an ox-bow of the Neckar near Heidelberg and famous for their jaw of *Homo heidelbergensis* (see p. 861), contains more than 120 plant species[324] and a rich mammalian fauna[325] characterised by Pliocene survivals, e.g. *Trogontherium cuvieri*, *Elephas trogontherii*, *Dicerorhinus etruscus*, *Hippopotamus major*, *Machairodus* sp., and by Pleistocene forms, e.g. *Elephas antiquus* and *Equus mosbachensis*, which place it in the first interglacial epoch[326] or in the Elster interstadial.[327] Rodents and other animals show that it is later than the Cromer Forest Bed.[328] Tegelen (see p. 1043) and Mosbach also by common consent belong to this interglacial horizon, as may, on pollen analytical grounds, Haren in the Ems valley,[329] Neu-Ohe on the Lüneburger Heide[330] and Hamarnia and Dzbanki in Poland.[331]

The travertine of Cannstatt, with its warm plants, snails and mammals, belongs to the Elster-Saale interglacial[332]—it is covered by an Older Loess—and that at Ehringsdorf (Lower Travertine) to the last interglacial[333]—it contains remains of Neanderthal man.

Skaerumhede series. One of the most critical bores through the European drifts is at Skaerumhede, north Jutland, where more than 200 m of drift was pierced in a search for oil—the Pleistocene organic remains give rise to natural gases (86–91% methane) at more than one hundred localities in north Jutland.[334] The succession in descending order was as follows[335]:

D. Fluvioglacial layers, 0–57·4 m.

Sand, clay, gravel, with overwhelming preponderance of boulders from south-east Norway (rhomb porphyry, laurvikite), formed by a short-lived advance of Baltic ice. Contains plant remains and rolled fragments of marine mollusca.

C. Marine Skaerumhede series, 57·4–180·3.

Contains shells *in situ* which are frequently well preserved, the young and smaller species often with closed valves. Shows change of temperature through a cold interglacial.

(c) *Portlandia arctica* zone (Older Yoldia Clay).

Up to the time of the bore, the oldest known glacial deposit in Denmark. Marine clay formed in a cold climate as shown by arctic molluscs and glaciated and ice-scoured boulders drifted from Norway. Intermixture of sand and gravel layers with shell fragments of chiefly mosses, occasionally seeds and remains of leaves of higher plants, including *Betula nana*, *Salix herbacea* and *S. polaris*.

(b) *Abra nitida* zone, 97–106 m.

Soft, dark clay without stones, containing boreo-arctic molluscs, such as live to-day at depths of 20–40 m on the coasts of west and east Finnmark.

(a) *Turritella terebra* zone, 106·4–180·3.

Soft clay, rich in boreal molluscs living to-day in depths of 40–80 m off west Norway and the Lofoten Islands.

B. Older Boulder-clay, with subordinate fluvioglacial beds, containing Baltic erratics, brought by the Older Baltic Glacier. The included molluscs (*Portlandia arctica, Tellina calcarea, Saxicava arctica*) are purely arctic, derived from some earlier marine deposits.

A. Chalk (*Belemnitella mucronata* zone).

The Skaerumhede series, which also includes beds in the drifts of other places in north Jutland[336] and in Sjaelland, Möen and Rügen[337]—the Elbing Yoldia Clay (see p. 946) may be the *Portlandia arctica* zone—belongs apparently to the retreat before the Baltic moraines[338] or the last or Eemian interglacial,[339] though recently the Skaerumhede series has been proved to lie between moraines C and D and therefore to be later than the Eem interglacial.[340]

The Eem interglacial was more continental than the present, as is suggested by the distribution of the blackearth "steppe islands" from the Rhine to Poland (see p. 916)—some of these are Boreal (see p. 1491)—and by the reddish soils of this age in south-west Germany, France and the Thames

valley which are reminiscent of the Mediterranean soils of to-day.[341] It was also apparently warmer than the present though a subarctic or minor cold phase, the Danish Middle Bed (the equivalent possibly of the cold phase of the flood loam and fourth glacial terraces of Ehringsdorf with mammoth and *Emys orbicularis* and of the intra-Monastirian fall of sea-level[342]) intervened in the middle of the epoch and is not to be correlated with any one of the four recognised glaciations (Elster, Saale, Warthe, Weichsel). To its interstadial deposits may belong the upper Travertine of Ehringsdorf. Nevertheless, no corresponding cold horizon is known from the north German succession or from any other area outside Denmark.[343] Since the north German Saale-Weichsel interglacial deposits show no sign of a second warm period the double period in Denmark may be due to later disturbances and solifluxion.[344]

To the Saale-Weichsel interglacial belong the various deposits near Berlin (Phoeben, Klinge, Rixdorf, Neukölln) with a warm mammalian fauna (*Elephas antiquus*, *Felis leo*, *Diceros merckii*) and a cold one (*Elephas primigenius*, *Tichorhinus antiquitatis*, *Ovibos moschatus*, *Rangifer tarandus*). The plants show a succession from arctic and subarctic through *Betula* and *Pinus*, mixed oak forest, *Carpinus*, *Picea* and *Abies* back to *Betula* and *Pinus*.

The "great" or Elster-Saale interglacial was likewise interrupted by at least one cold phase which may have been the first phase of the Saale glaciation.[345] It may be represented by the second glacial terrace of Thuringia and other areas (see p. 1267), the middle Older Loess (see p. 1027), and certain pedological evidence in north France.[349]

Danish terrestrial interglacial deposits. Terrestrial interglacial deposits in Jutland[347] are found in basins into which they thicken from the sides. They occur without or within the limit of the last glaciation, without, covered with solifluxion material, within, buried beneath true drift, as at Ejstrup, Rostrup, Vellow, Trelde, Fredericia, Vejle and Horup[348] (fig. 186).

Outside the moraines, the deposits are of two types. The first or Herning type consists of bogs in hollows with two temperate beds, as at Nörbolling, Brörup Hotel Bay and at Herning itself, in which the succession is as follows:

Solifluxion layer of stoneless clay, sand or gravel with interkneaded lumps and lenses of interglacial mud and peat and destitute of stratification, coeval with the last glaciation of Jutland.

Clay bed or *Betula nana-Empetrum* heath, a repetition of the Middle Bed, with *B. nana*, *B. pubescens*, *Empetrum nigrum* and aquatic species.

Upper Mud Bed, almost the same species as the Lower Mud Bed (*Brasenia purpurea*, *Dulichium spathaceum*, *Trapa natans*, *Tilia platyphyllos*, *Carpinus betulus*, *Taxus baccata*).

Middle Bed with subarctic flora of *Betula nana*, *Empetrum nigrum*, *Salix* sp. and wind-carried pollen of trees far away (*Carpinus*, *Corylus*, *Quercus*) and a July temperature of 12·7°C.

Lower Mud Bed consisting of an upper *Picea-Carpinus* zone and a lower *Betula* and *Pinus sylvestris* zone separated by mixed oak forest (*Quercus robur*, *Alnus glutinosa*, *Ulmus*, *Corylus avellana*, *Fraxinus*, *Ilex aquifolium*, *Tilia platyphyllos*) which represents the Eem zone.[349]

Arctic clay with *Salix herbacea*, *S. reticulata*, *Betula nana* and arctic mosses resting on moraines.

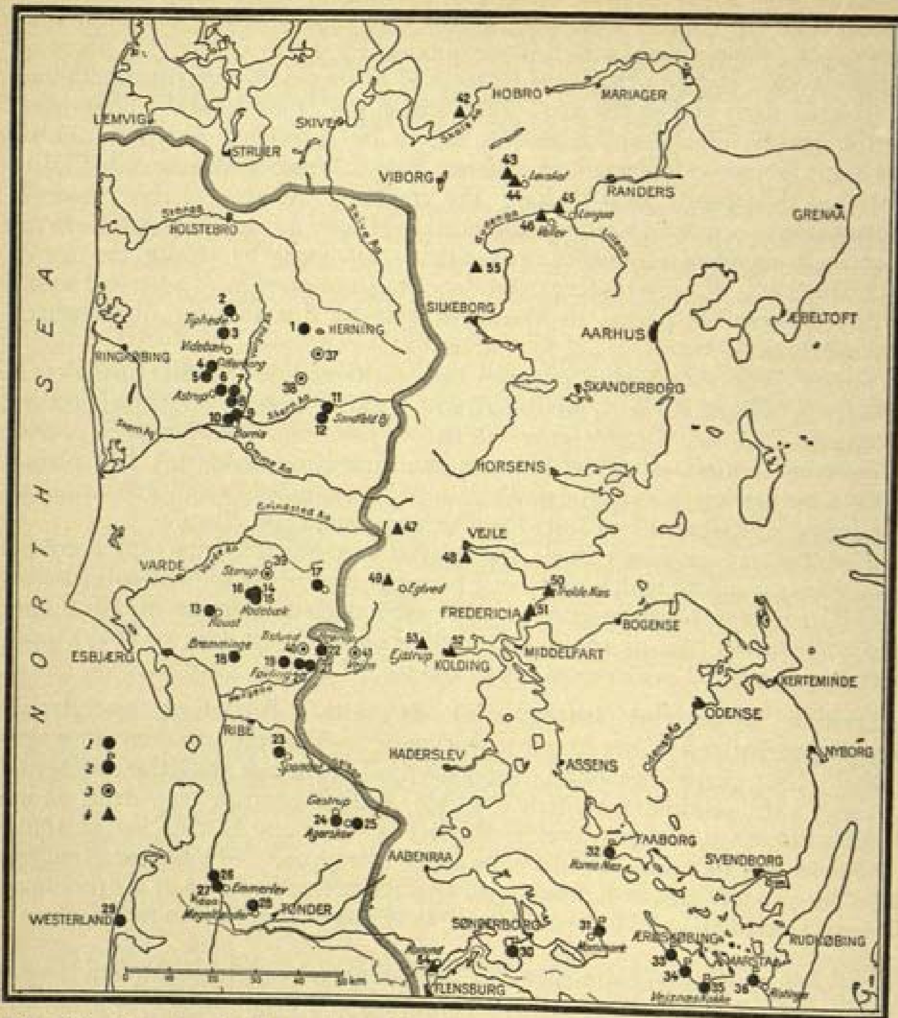

FIG. 186.—Map showing the position of the chief interglacial freshwater deposits in Jutland, Fyn and Danish islands and the limit of the last glaciation. 1, deposits of the Brörup type and of the Herning type (last interglacial) Nos. 1–29; 2, freshwater deposits associated with dislocated Eemian strata (last interglacial) Nos. 30–36; 3, deposits from penultimate interglacial epoch, Nos. 37–41; 4, interglacial freshwater deposits covered by materials of the last glaciation, Nos. 42–55. K. Jessen & V. Milthers, *854*, pl. I (Atlas).

The second or Brörup type has only one temperate interglacial layer, i.e. the upper part only of the Herning succession, as the following sequence at Solsö reveals:

Solifluxion cover of arctic climate.
Layer in which *Pinus* replaces *Picea* and *Betula nana* reappears and forms moors.
Mixed oak forest with *Corylus* and *Quercus* followed by *Carpinus* and *Picea*.
Tundra vegetation of *Dryas octopetala*, *Betula nana*, etc.

The Brörup type is also seen in several places on Sylt, e.g. the Tuul of Sylt,[350] in Schleswig-Holstein, the Hamburg district, e.g. Kuhgrund I (as C. Gagel, J. Stoller and W. Wolff recognised), Kuhgrund II (Lauenburg), previously regarded as postglacial[351] or interstadial,[352] at Römstedt and Fleestedt in the Lüneburger Heide[353] and in east Germany and Poland.[354] The second warm period of the bipartite interglacial (see above) of the Herning type may be due to contamination from the earlier horizon.[355]

The Esbjerg Clay,[356] with *Yoldia arctica* and a specifically poor fauna, lies undisturbed in a basin in the moraine. Partially buried under fluvioglacial and morainic sands, it dates from the Elster-Saale or penultimate interglacial[357] to which the flora of the mud blocks found in a secondary position near Copenhagen also probably belong.[358] Mammoth remains have been found in Denmark including Sjaelland.[359]

The interglacial epochs have been denoted[360] the Holstein and Eemian or Paludina and Rixdorf, with the Tiglian and Cromerian preceding them. Alternatively, they have been named the Bel (Baltic-Elster), Es (Elster-Saale), Saw (Saale-Warthe) and Waw[361] (Warthe-Weichsel); or termed I-interglacial (Lat. *infirma*), O-interglacial (Lat. *optima*) and U-interglacial[362] (Lat. *ultima*) or Ilm, Orla and Unstrut from the three Thuringian rivers.[363] They have also been lettered C (Cromerian), D (Dürnten or Needian of Holland) and E (Eemian)—A was assigned to the older Villafranchian (Günz interstadial), B to the younger Villafranchian and F to the Aurignacian oscillation,[364] W1–W2 (see p. 1047).

The horizons in Germany may be correlated as in the following table:

CORRELATION TABLE

	Lower Rhine and Netherlands	*North-west Germany and Denmark*	*Thuringia and Saale*	*Saxony and Brandenburg*	*West and East Prussia*
Weichsel	Lower Terr. Tubantian	Drift and younger loess	Drift and younger loess	Drift and younger loess Borna	Drift and younger loess
Saw	*Eem Sea*	*Skaerumhede Eem Sea; Winterhude; Kuhgrund I and II Lüneburg kieselgur*	*Rabutz clay Tufas of Weimar, Taubach and Ehringsdorf*	*Rixdorf Phoeben, Klinge*	*Elbing clays*
Saale	Middle Terr. Drenthian	Drift and Older loess	Drift and Older loess	Older loess	Older loess
Es	*Holstein Sea Paludina beds*	*Holstein Sea Krefeld Beds*	*Frankenhausen gravels*	*Markkleeberg*	
	Needian	*Heligoland Töck*	*Paludina beds*	*Paludina beds*	*Paludina beds*
Elster	Main Terr. Taxandrian	Lauenburg clay (?) Drift			
Bel.	*Tiglian*		*Preglacial Terr. I. Süssenborn*		
Baltic	Icenian	Sylt Crag Elbe (?)	Preglacial Terr. II–IV		

5. *Poland, Russia and Siberia*

The zonal distribution of the landscape which characterises north Germany is found in Poland, together with the three zones relative to the loess—complete failure of loess in the north, island-like occurrences in a middle zone, e.g. near Nowogrodek and Pinsk, and a southern zone of continuous loess. Nevertheless, the number of glaciations in Poland and the territory of the U.S.S.R. is still uncertain. While a double glaciation ("Carpathian" and "Central") is postulated by some Polish (see p. 671) and Russian geologists[365] —especially before the discovery in 1930–1 of a number of fossiliferous beds in different parts of Poland—and is established for many localities,[366] other glacialists demand three[367] (named Likhvin, Dnieper-Don and Valdai), four[368] or even five[369] or six (p. 922) glaciations, according apparently to the region in which they have worked—the fifth is the Néowürm. The equivalent of the Günz is unknown in Russia[370] though W. Krokos[371] recognised six loess horizons in the Ukraine which he correlated with the alpine four, a

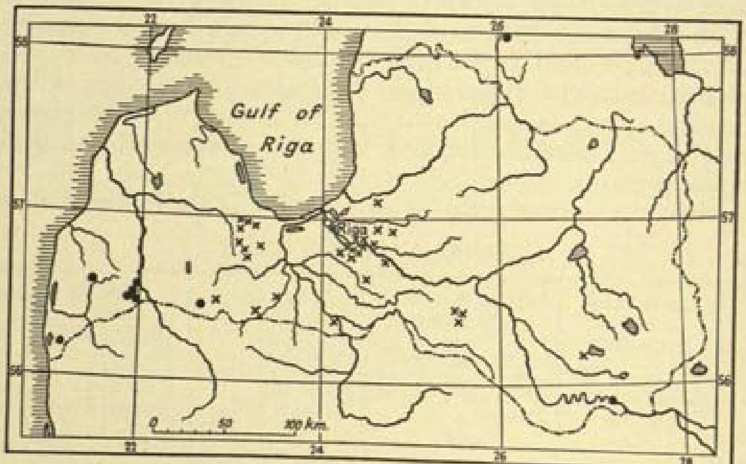

FIG. 187.—Interglacial deposits (black circles) and *Portlandia arctica* in secondary deposits (crosses) in Latvia. A. Dreimanis, *G. F. F.* 71, 1949, p. 535, fig. 5.

pre-Riss glaciation and Würm 2. W. Szafer and other geologists,[372] on the basis of the interglacial floras, have recognised for Poland four glaciations, named Jaroslavian, Cracovian (= Carpathian), Warsovian I and Warsovian II (this comprises the zone of fresh topography and abundant lakes) which they correlated with the four German and Alpine glaciations[373]—the interglacial phases were named Sandomirian, Masovian I and Masovian II. Two glaciations earlier than the Central Polish glaciation (Saale) are recognised.[374] An interglacial, which preceded the Elster glaciation and was roughly coeval with the Cromerian, occurred at Hamarnia in Galicia,[375] and two interglacial horizons are known from Latvia[376] (fig. 187).

Each of the interglacial horizons in Poland has its own peculiar cycle of climatic changes and its own characteristic pollen diagrams (see figs. 172b and 172c, pp. 908, 909) so that even a small fragment of these interglacial stages may determine by itself the relationship and geological age of the deposit. W. Szafer (1952) has recently described the successions. The

Masovian II, which occurs in at least 30 sites, has four stages; stage I is a coniferous forest (*Pinus sylvestris, P. cembra, P. montana, Larix polonica, L. sibirica, Picea excelsa, P. obovata*) with an admixture of birch (*Betula pubescens, B. tortuosa*); stage II begins with a decrease of these species and a rapid immigration of *Quercus, Corylus, Ulmus* and *Tilia*, with *Acer platyphyllos, A. tataricum* and *Fraxinus*—the abundance of *Corylus* distinguishes this interglacial from the earlier interglacial epochs and from the Holocene in Poland—and with water-plants including *Brasenia purpurea, B. nehringi, Dulichium spathaceum, Trapa natans* and *Aldrovanda vesiculosa*; stage III, with a more humid and cooler climate, is characterised by *Carpinus betulus* and *Abies pectinata* and a striking absence of *Fagus*; stage IV, with a marked cooling of the climate, shows an increase of *Picea obovata, Pinus, Betula* and *Salix* and a re-appearance of a treeless tundra with *Betula nana* and NAP.

Masovian I is distinguished by the almost constant predominance of conifers *Picea excelsa, P. omorica, Pinus, Abies fraseri* (North America tree), with *Larix*; stage I has *Pinus cembra, P. sylvestris, Larix* cf. *polonica, Picea excelsa, Abies fraseri* and *Betula*; stage II shows a decrease of *Pinus* and *Betula*, an enhanced importance of *Picea* (*P. excelsa, P. omoricoides*) and appearance of *Quercus, Tilia, Ulmus* and *Corylus*—the latter, in contrast to Masovian II, nowhere has a high percentage; stage III, the thermal optimum, with *Abies fraseri, Carpinus betulus* and *Quercus*—there was, however, no EMW—and water-plants as in Masovian II; stage IV, shows a sudden increase of *Pinus* and *Betula*.

The Polish interglacial deposits also reveal the disappearance of the extinct species and those still living in North America or east Asia (Szafer, 1952)—the Mindel (Cracovian) glaciation was catastrophic in this respect. Thus of the 11 extinct species which were present in the first interglacial, e.g. at Mizerna, two only are present in the second interglacial (*Picea omoricoides, Vaccinium* cf. *priscum*) and none in the third interglacial, while the corresponding numbers for the North American-east Asian species were 15, 6 (*Tsuga* sp., *Abies fraseri, Osmunda claytoniana, Azolla filiculoides, Dulichium spathaceum, Brasenia purpurea*) and 2 (*Dulichium spathaceum, Brasenia purpurea*).

Four glaciations, equated with the German or Alpine four, are claimed for the Caucasus.[377]

The penultimate glaciation in Russia appears to have been the maximum[378] (N. Florow and others placed this in the last[379])—the Scandinavian and Ural-Timan ice-masses were then united[380]—while the equivalent of the German Elster glaciation may be seen in the drift profile at Likhvin in central Russia.[381]

Russia's last glaciation was double,[382] to judge from its valley excavation and aggradation, and its loess and terraces which have been classified as Würm 1 and 2 or Würm or Néowürm, though G. Mirčink[383] recognised four stages of this glaciation and I. W. Danilowsky[384] three. The entire development of the Palaeolithic from Mousterian to Magdalenian in Russia and north Asia belonged to this glaciation[385]—lower Palaeolithic occurs in the Crimea.[386] The Moscow moraines are usually regarded in Russia as equivalent to the Weichsel and the Valdai moraines to the Warthe.

The limits of the glaciations are as uncertain as their number. Woldstedt's reconstruction is given in the map[387] (fig. 188). The boundary of the last glaciation, the subject of many discussions,[388] is the outermost line of the

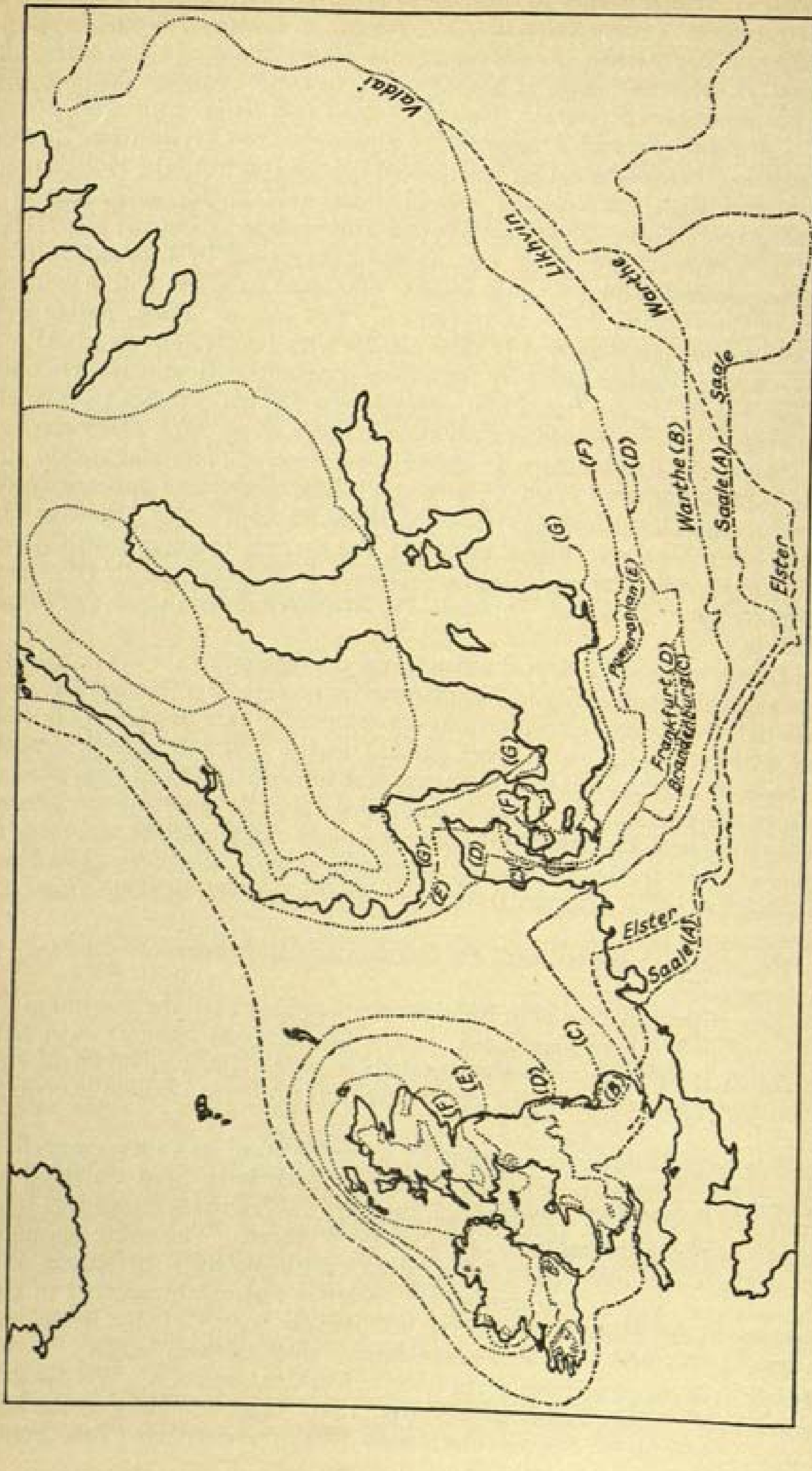

FIG. 188.—Extent of the different ice-sheets in Europe.

lake-region (*Kleinseegebiet*[389]), just as it is in north Germany. While the details remain to be discovered, its general course is known[390]; it runs through north Poland from south-west of Vilna to north of Minsk, thence eastwards and north-eastwards through the west Russian Ridge to the west of the Valdai Hills (56° 45′ N.; 33° E.), and by the northern lake-region to the east of the White Sea. H. Wilhelmy[391] has reconstructed the distribution of the

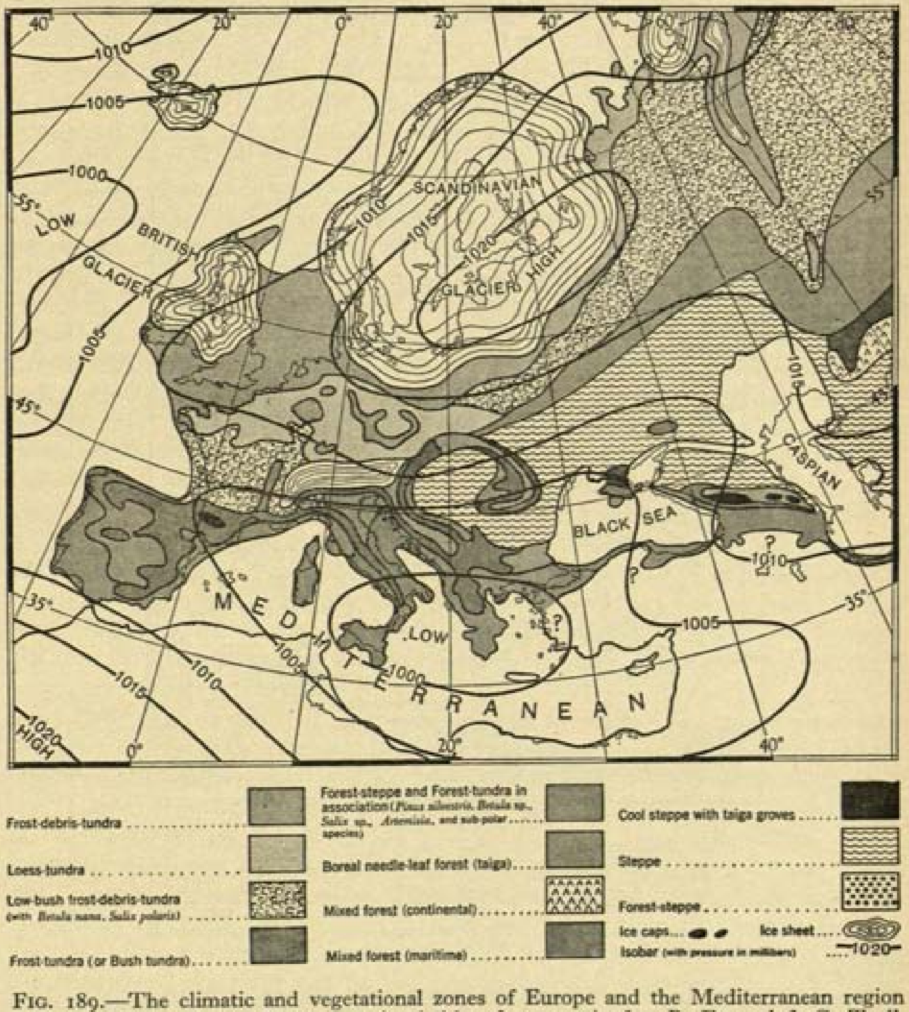

FIG. 189.—The climatic and vegetational zones of Europe and the Mediterranean region during Würm times. Vegetation (probably of summer) after B. Frenzel & C. Troll, *E. & G.* 2, 1952, map opp. p. 160; distribution of cyclones and anticyclones after H. C. Willett, *G. Ann.*, 32, 1950, fig. 1, facing p. 180. Redrawn by F. K. Hare, *Arctic*, 6, 1953, p. 59, fig. 1.

vegetation at that time in eastern Europe, H. Poser[392] has marked out the climatic provinces for the whole of Europe and J. Büdel[393] has extended these zones into the Mediterranean region (fig. 189).

Interglacial plants, whose distribution is shown in the map[394] (fig. 190), have been found in numerous localities, including Latvia[395] and Estonia[396]

and the Governments of Kaluga, Minsk, Smolensk and Grodno. Those at Grodno, Szezercowa, Kraslava, Duna, Deseln and Leningrad are mostly referable to the last interglacial,[397] whose flora embraces more than 25 species of moss and 125 species of flowering plants, including the water-plants *Brasenia purpurea*, *Trapa natans*, *Naias marina* and *N. flexilis*, and indicates a

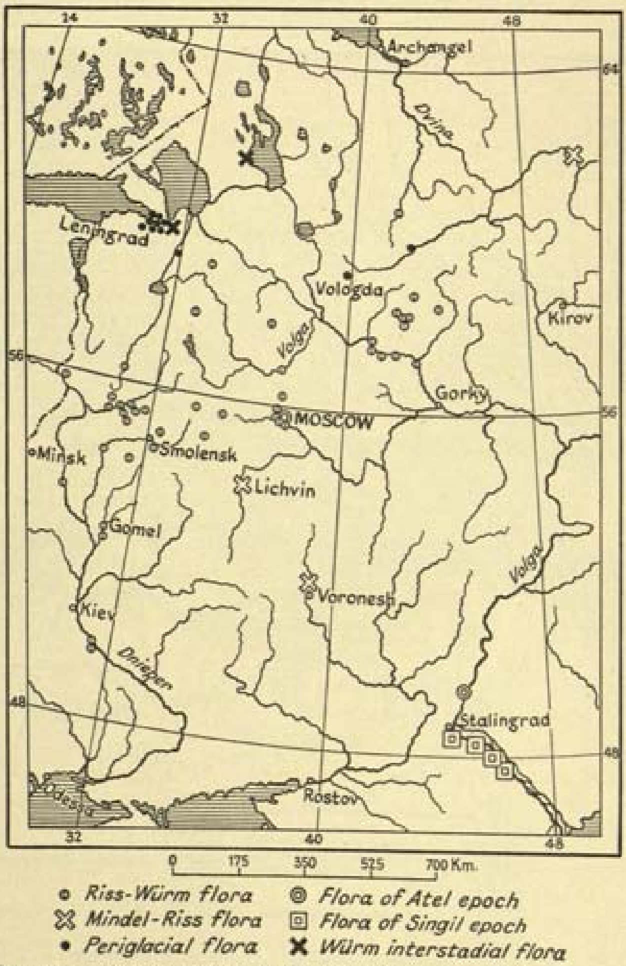

FIG. 190.—Distribution of the floral localities of the Pleistocene in European Russia. W. N. Sukatschew, *148*, p. 78.

temperature higher than that of the postglacial climatic optimum.[398] The celebrated plant bed of Likhvin south of Kaluga (see above) belongs to the Mindel-Riss[399]; it records a climatic change from cold back to cold through a moister and warmer period (though in only one instance is an interglacial deposit known with an arctic tundra containing *Betula nana*[400]). Different workers have referred this horizon to each of the three recognised interglacial epochs. The *Paludina* horizon is found in Poland and below the "boulder sands" of the Dnieper lobe in the Ukraine and in other places, proving that as in Germany the mass occurrence of *Paludina diluviana* is an essential feature of the antepenultimate interglacial[401] (see p. 949).

Few interglacial localities are known from eastern Russia[402] and the sole deposit in Poland belonging to the oldest interglacial that has been examined occurs at Hamarnia near Jaroslaw (see p. 949).

A Pliocene flora,[403] with many Asian and North American types, has been discovered in the Voronesch region and in the Caspian area (Aktschagyl Beds).

On the whole it would appear that at least three glaciations have been demonstrated by interglacial horizons[404] and by three loess horizons in the blackearth region.[405]

Boreal transgression. A marine transgression, familiar to early geologists[406] from its clays around the White Sea and along the Murman Coast, is now known to have affected the coastal areas, estuaries and lower parts of the valleys of wide regions[407] (fig. 191). It submerged the north coast of the Old World[408] and the off-lying islands,[409] including the New Siberian Islands and Severnaya Zemlya and the islands north-east of Novaya Zemlya. It inundated the Petschora and Timan regions, surrounded the Byrranga Plateau in the Taimyr Peninsula as an island, covered all the Jamal Peninsula and parts of the Gydan Peninsula, and flooded the valleys of the Lena and the Yenisei to 67° 31′ N., the Dwina to 62° N., the Petschora to 65° N., and the Lower Ob to 61° N. On the east, it covered a coastal strip in north-east Asia including the east coast,[410] e.g. the coasts of the Sea of Okhotsk and the Bering Sea, converting Sakhalin into an archipelago of small hilly islands,[411] but avoiding Kamchatka.[412] On the west it reached the Kola Peninsula,[413] Lake Onega and the Dwina[414] (including the Waga), probably joining the Baltic[415] or Eemian Sea over Leningrad where Yoldia Clays are associated with freshwater beds containing diatoms[416]—Fennoscandia was then an island—and may have extended to Velfjord[417] and the Tromsö area where (at 42 m O.D.) interglacial littoral molluscs (*Mya truncata, Littorina rudis*) *in situ* have been found.[418] On the south it may have submerged the watershed north of the Caspian Sea[419] (though there is no proof of this; see p. 1132) and have spread into Lake Baikal.[420]

Its later part, the Portlandia Sea,[421] passed over the Carelian isthmus into the Gulf of Finland, spread through the Baltic to Möen and Rügen,[422] and the celebrated Elbing Yoldia Clay (see p. 946). Pebbles and boulders of a clay containing marine diatoms in an os at Rouhiala[423] outside the Salpausselkä in south-east Finland belong here. They indicate an open, relatively deep and cold sea, though pollen grains of *Carpinus, Betula, Pinus* and *Corylus* imply a maritime climate, probably more favourable than the postglacial climatic optimum (see p. 1493). In all probability they belong to the later part of the succession represented at Mga near Leningrad[424] which has the whole development of the last interglacial, viz. two cold (but not tundra) periods parted by a warm period. The age of the Mga beds, however, is not certainly known—they have been placed in the Mindel-Riss, Riss-Würm and (with less likelihood) in the Würm interstadial. A similar interglacial, with early and late colder and more shallow phases, is known from the White Sea basin.[425]

This Boreal sea, which corresponds to the "White Sea transgression" of K. A. Wollosowitsch and (as Munthe[426] and others[427] surmised) to the Skaerumhede Series, was colder in the east than in the south Baltic. It was separated from the warm Eemian Sea both in Denmark and north Russia by an advance of the ice with a subarctic flora,[428] the advance being the Warthe

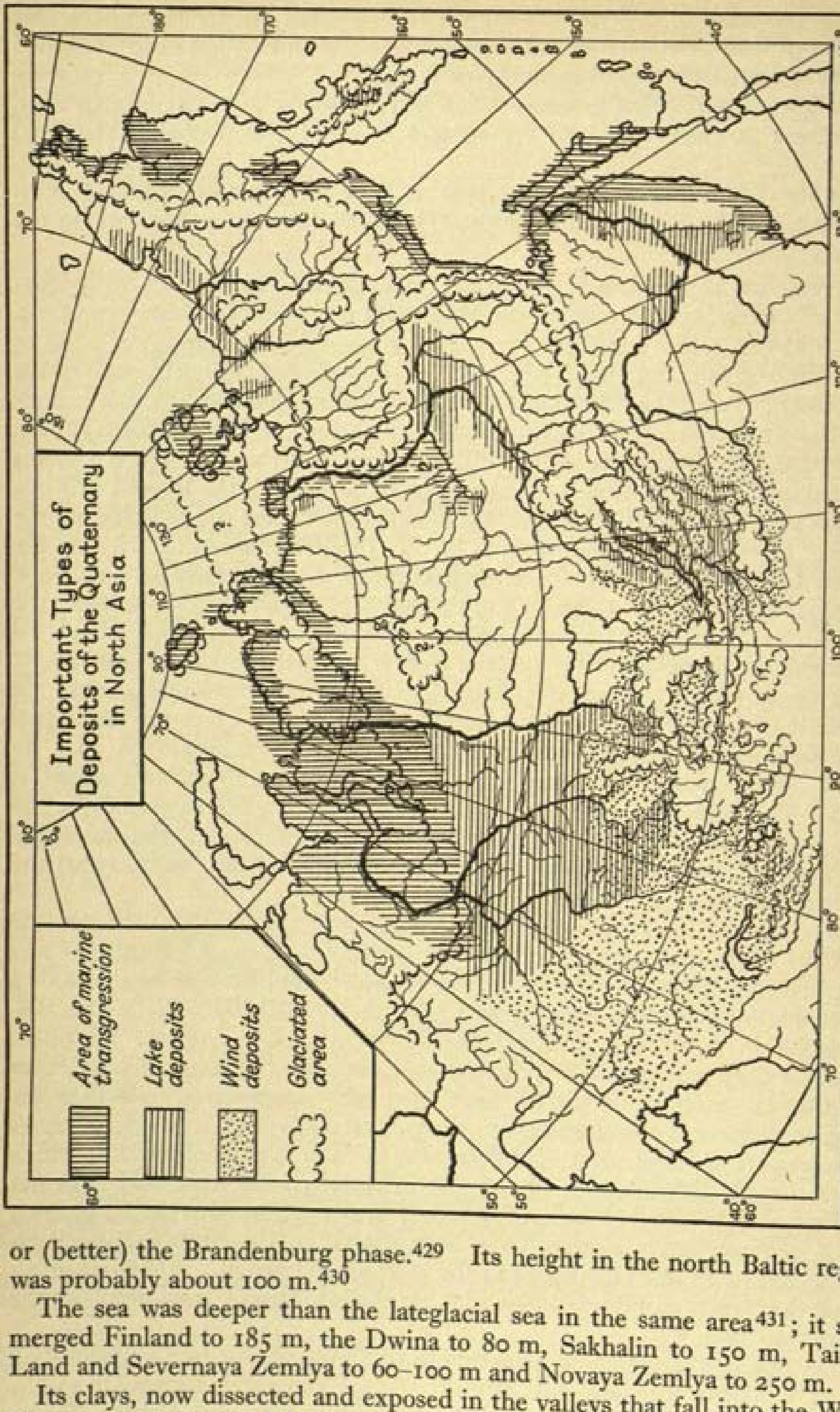

FIG. 191.—Map of the Boreal transgression, limnic deposits, aeolian deposits and glaciated regions in north Asia. W. A. Obrutschew, *1221*, pl. 10.

or (better) the Brandenburg phase.[429] Its height in the north Baltic region was probably about 100 m.[430]

The sea was deeper than the lateglacial sea in the same area[431]; it submerged Finland to 185 m, the Dwina to 80 m, Sakhalin to 150 m, Taimyr Land and Severnaya Zemlya to 60–100 m and Novaya Zemlya to 250 m.

Its clays, now dissected and exposed in the valleys that fall into the White Sea and Arctic Ocean, are 76 m thick at Archangel and enclose a warmer fauna than these seas have to-day[432]: it includes *Cardium edule*, *Mactra elliptica*

and *Astarte sulcata* which no longer live on the north Russian coasts. The sea was open and ice-free, though glaciers may have entered it in the Taimyr Peninsula.[433] During the cycle, the climate passed from arctic to boreal and back again to arctic[434] while the limnic, fluviatile and terrestrial nature of the uppermost intermorainic layers, with their plants and freshwater molluscs, found for example in the lower Dwina and Leningrad area, prove that the sea had retreated before the ice began to advance.[435] Relics of the transgression are the *Yoldia arctica* fauna of the White Sea according to N. Knipowitch (cf. p. 1414) and the halophytes, e.g. *Artemisia rupestris*.[436]

Since the clays everywhere rest on an older drift, as T. Tscherhyschew[437] early noticed, they were thought to be the equivalent of the lateglacial Yoldia Clays, though Murchison[438] showed as early as 1845 that sands, gravels and erratics cover them. They are indeed overlain by boulder-clay or "marine moraines" (with shells) and are plainly interglacial.[439] This fact, first recognised by De Geer,[440] has been demonstrated for the Kola and Kanin peninsulas, for the lower Dwina, lower Ob, lower Petschora, Severnaya Zemlya, New Siberian Islands and at Ingria on the Russo-Finnish frontier. The overlying moraines in the Leningrad area are dark grey with organic matter from the interglacial deposits and contain erratics of *Paludina arctica*.[441] Nevertheless, some, re-affirming that the trangression was postglacial,[442] allege that the upper boulder-clay is not a true till but, as its structure and marine fauna imply, a product of drift-ice. Others recognise two transgressions, corresponding to the Mindel-Riss and Riss-Würm interglacials[443] or to the beginning and close of the latter.[444]

In Siberia, the number and extent of the glacial epochs are still very uncertain and the age of the interglacial beds with plants and mammoth remains between the ice-layers (see p. 650) in the New Siberian Islands is still to be determined. Russian geologists usually regard the main interglacial as Riss-Würm. The succession has recently been given as follows[445]: Günz-Mindel, fauna of Ischim (?); Mindel glaciation, 100 m terrace of the Angara and Yenisei valleys and the sands of Pawlodar with *Elasmotherium* sp.; Mindel-Riss, upper terrace of Ischim with *Alce latifrons*, *Elephas* sp.; Riss glaciation of Golez Mountains, Altai and Sajan, union of Ural glaciers and North Siberian ice (from Novaya Zemlya and Taimyr) on the west Siberian plains south of 60° N. Lat., with a chain of glacier-lakes to the south draining by the Turgai depression into the Aralo-Caspian Sea (see p. 1131); Riss-Würm, Boreal transgression; Würm glaciation, local glaciers in mountains with mammoth fauna—the lowlands were ice-free. The two extensive glaciations, represented by two drifts and by lenses of fossil ice, have to the south of them and of 58–60° N. Lat. two loess horizons with a cold fauna.[446] One reconstruction is shown in the text-figure (fig. 192) which should be compared with figs. 131, 132 and 133.

Correlation Table of Scandinavian Ice-sheet

(interglacial units are printed in *italics*)

Germany	*Poland*	*European Russia*
Brandenburg	Warsovian 2	Valdai
Eemian: Rixdorf	*Masovian 2*	*Valdai-Dnieper*
Saale	Warsovian 1	Dnieper-Don
Holstein: Paludina	*Masovian 1*	*Likhvin-Dnieper*
Elster	Cracovian	
Elbe	Jaroslavian	

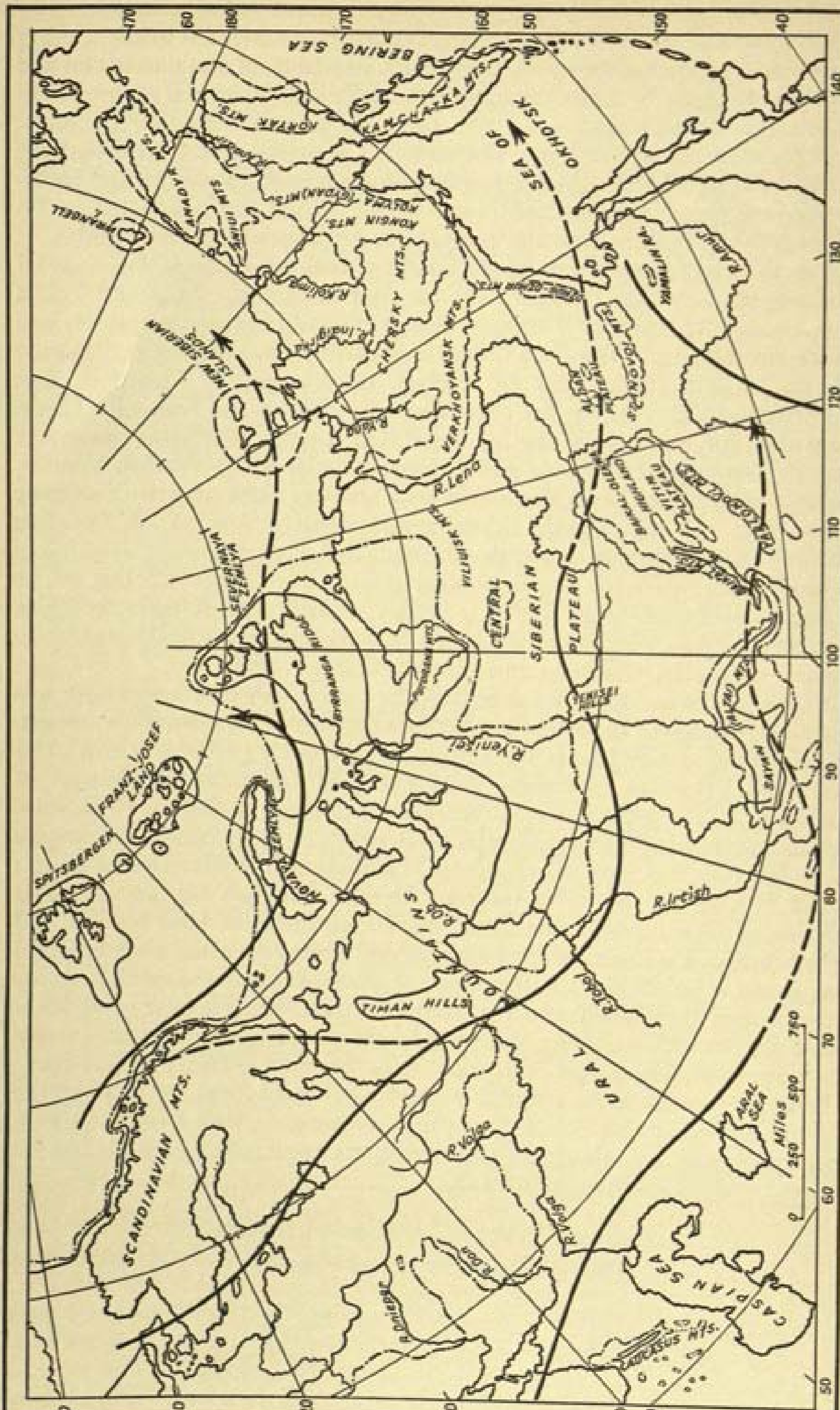

FIG. 192.—Glaciation of Siberia: continuous line, outer limit of last glaciation; dot-dash line, limit of maximum glaciation; dash-line, outer limit of ice in east Siberia (age undetermined); arrows, storm tracks of to-day. R. A. Flint & H. G. Dorsey, 575, pl. I (opp. p. 106).

6. *Fennoscandia*

Interglacial occurrences. Interglacial deposits in Fennoscandia are scarcely to be expected: the position was central and the seat of maximum ice-erosion. Nevertheless, interglacial stream courses in the bottom of U-valleys have been recognised,[447] marine caves of interglacial age have been discovered,[448] and two or three glaciations have been postulated.[449] E. Ljungner[450] recognised (1) an older cirque glaciation (submarine cirques) in coastal mountains north of the Arctic Circle, (2) a stage of western or Atlantic icesheet with an iceshed to the west of the watershed, (3) a continental glaciation with the iceshed to the east of the watershed—during the passage from stage (2) to stage (3) striae were turned clockwise from north-west to north and north-east and finally to south-east. The later glaciation also began with a mountain phase.

L. Holmström[451] was led to the idea of bipartition by discovering fresh-water species between boulder-clays at Klägerup, though G. Erdmann[452] considered their significance to be local. G. De Geer,[453] however, was the principal exponent of Scandinavia's glaciation by two icesheets (Hansen's "deuteroglacial" and "proteroglacial"[454]), though he arrived at his conclusions chiefly from the erratics in the drifts.

The modern view of bipartition for the peninsula—the two glaciations are usually termed the "great" and the "last"—rests on the distribution of mammoth remains and of fossiliferous layers between the drifts. Mammoth bones, teeth or tusks, belonging probably to *Elephas primigenius sibericus*, have now been found in eleven localities in Scandinavia[455]—two new mammoth finds, with pollen of *Pinus*, *Picea*, *Alnus*, *Betula*, etc., have recently been discovered in Ångermanland[456]—and in seven localities in Finland[457] (fig. 193). Two of the places, namely, Fröso and Vagre (Dovre), are practically on the Pleistocene iceshed. Vertebrae of musk ox[458] have also been discovered south of Trondheim and at other places in Norway and at Bohuslän. *Lemmus lemmus* was also a member of this interglacial fauna.[459]

While monoglacialists regard these animals as preglacial[460] and P. A. Øyen[461] makes them postglacial, the musk ox in his opinion surviving into the *Mytilus* and the mammoth into the *Portlandia* epoch (J. E. Rosberg[462] thought the Finland mammoth was later than the Salpausselkä) most geologists[463] place them in an interglacial epoch, either the Mindel-Riss[464] or the Riss-Würm.[465] Mammoth, for example, did not range backward into preglacial time (see ch. XXXIV) and the lateglacial submergence rules out a postglacial survival in some localities.[466]

The interglacial fossiliferous deposits, which are generally absent from Scandinavia because of the severer erosion in this region,[467] include, among a number of Norwegian and other occurrences,[468] the Lomma clays[469] of Scania which rest on the chalk, though a lateglacial or postglacial date[470] has been assigned to them. They also comprise beds with a rich flora and fauna at Robertsdal[471]; freshwater *gyttja*, 0·7–3·0 m thick, which is covered by 2·5–5·0 m of boulder-clay at Hernösand[472] near the iceshed at 5 m A.S.L. and contains freshwater diatoms, mosses and phanerogams, and insects, now almost all extinct, signifying a somewhat warmer climate than now (also referred to preglacial[473] or postglacial[474] times); beds with temperate plants, suggestive of a warmer climate, discovered in Västergotland[475] or found under boulder-clay (possibly slipped[476]) at Bollnäs near the iceshed in south

Norrland at 96 m[477]; mud with remains of insects, lacustrine diatoms and pollen of *Betula*, *Pinus* and *Picea* near Långsele in Ångermanland[478]; beds with insects in other places[479]; marine clays with *Macoma calcarea*, *Cardium fasciatum*, *Mytilus edule* and *Abra longicallis*, found beneath moraines 3 m thick[480]; shelly clays below moraines at Slinningen near Aalesund[481] which have been attributed to creep[482]; sands and clays with worm tracks, snails,

FIG. 193.—Distribution of interglacial deposits and mammoth remains in Baltoscandia. R. Sandegren, *Natur i Ångermanland och Medelpad*, Uppsala, 1953.

plants (pollen of *Pinus*, *Picea* and *Betula*), and fish at 400 m in Jämtland,[483] overlain by moraines with a mammoth tusk; an interglacial horizon near Rouhiala in south-east Finland[484] (see p. 959) and an interglacial shore-line at 200 m in west Finnmark[485]; and, possibly, varve clays below ground-moraine, 30 m thick, at Hantula in south Finland.[486]

These fossiliferous deposits are mostly of uncertain age. Some no doubt are interstadial,[487] as suggested for Tornea, Bollnäs and Hernösand by G. Braun[488] and demonstrated for the Bergen district[489] where the ice over-

rode shelly deposits of a boreo-arctic character. Boreal species sandwiched between morainic drifts in Finland may be interglacial or related to slight advances on to a glacial tundra.[490] Double ground-moraines have also been correlated with separate glaciations.[491]

Extinct insects, discovered at Alnarp (see p. 281) with vegetable matter consisting of Tertiary and arctic plants (*Betula nana*, *Salix polaris*, *S. reticulata*) and molluscs, are referred by some to a preglacial "amber" river or lake, by others (and more probably) to an interstadial[492] or interglacial horizon.[493] The Lyngby culture (see p. 878) has been put in the last interglacial epoch.[494]

Although, as has been said,[495] no *mild* climate has yet been proved for Scania or any other interglacial bed of irreproachable character from any place nearer to the ice-divide than Jutland, recent research, including the definite discovery of mammoth and reindeer remains below the ground-moraine of the last glaciation,[496] tends to confirm the belief in at least one Fennoscandian interglacial epoch.

***Övervintrings* hypothesis.** R. Sernander[497] in 1896 suggested that a part of Scandinavia's *fjellflora* might have lived through the last glaciation in ice-free areas in Norway, and A. M. Hansen[498] in 1904 thought a stretch of Norway's west and north-west coast had floral refuges during the last glaciation—A. Blytt[499] had suggested in 1893 that the Greenland-American floral element was the oldest in the country. This theory of "hibernation" or "over-wintering" (*övervintring*), i.e. the persistence of plants, animals and man from the last interglacial in Fennoscandia, has found much support. It rests upon a variety of evidence, including the following: unglaciated lands, e.g. Mageröya, occur off north Norway[500]; intensely weathered and frost-shattered tinds are found in west Norway, e.g. Romsdalhorn, Trolltindene and Venjetindene; certain areas in Finnmark, Vesterålen, Tromsö region, including Varanger Peninsula, Duksfjell, Porsangerfjord and Altafjord districts and in south Norway, were ice-free during the last glaciation[501] (cf. p. 1171); marine deposits with temperate molluscs underlie moraines of the fjord glaciation (*Fjordtida*) in several places in Norway,[502] e.g. Jaeren, Karmöy, Möre and Tromsö, and temperate plants are found in similar circumstances[503]; certain strandlines in north Norway (lettered *l* to *p* by V. Tanner) preceded the lateglacial or postglacial features[504]; and warm littoral shells, e.g. *Venus casina*, deemed to be interglacial,[505] are dredged from 180 m off west Norway.

Most emphasis, however, has been placed on Norway's remarkable *fjellflora*[506] which, it is said, survived from the last interglacial[507] with insects and other forms. It contains species whose nearest living relatives are in Tyrol, Riesengebirge (e.g. *Hieracium tubulosum*), east Carpathians (e.g. *Taraxacum reichenbachii*), east Siberia (e.g. *Hieracium kuusamoense*) or North America (e.g. *Poa caespitans*), and is now either "bicentric", being restricted in Norway to an area near Stavanger about Dovre and Jotunheim ("Ilex flora"[508]) and to a second region north-east of Tromsö towards east Finnmark, or confined to one or other of these regions—the "northern unicentric" or "southern unicentric" forms (fig. 194). Some of the bicentric species and species groups, e.g. *Arenaria* and *Papaver*, have undergone some taxonomic differentiation. The rich "Hieracium flora", with *Rhododendron lapponicum*, *Arenaria humifusa*, *Braya purpurascens*, *Scirpus pumilus*, *Artemisia norvegica* and *Papaver radicatum*, is also concerned. Besides the arctic, the alpines and sub-arctics survived[509]—the ice in Fennoscandia, north of the Salpausselkäs,

lacked a marginal tundra[510] (see p. 1411). Even the "Atlantic" plants and the Norwegian spruce (*Picea abies*) were thought to have persisted,[511] though this is improbable—they migrated postglacially.[512]

The zoologists were more hesitant: the first to advocate this view was L. Stejneger[513] who was followed by J. S. Schneider.[514] Confirmation was

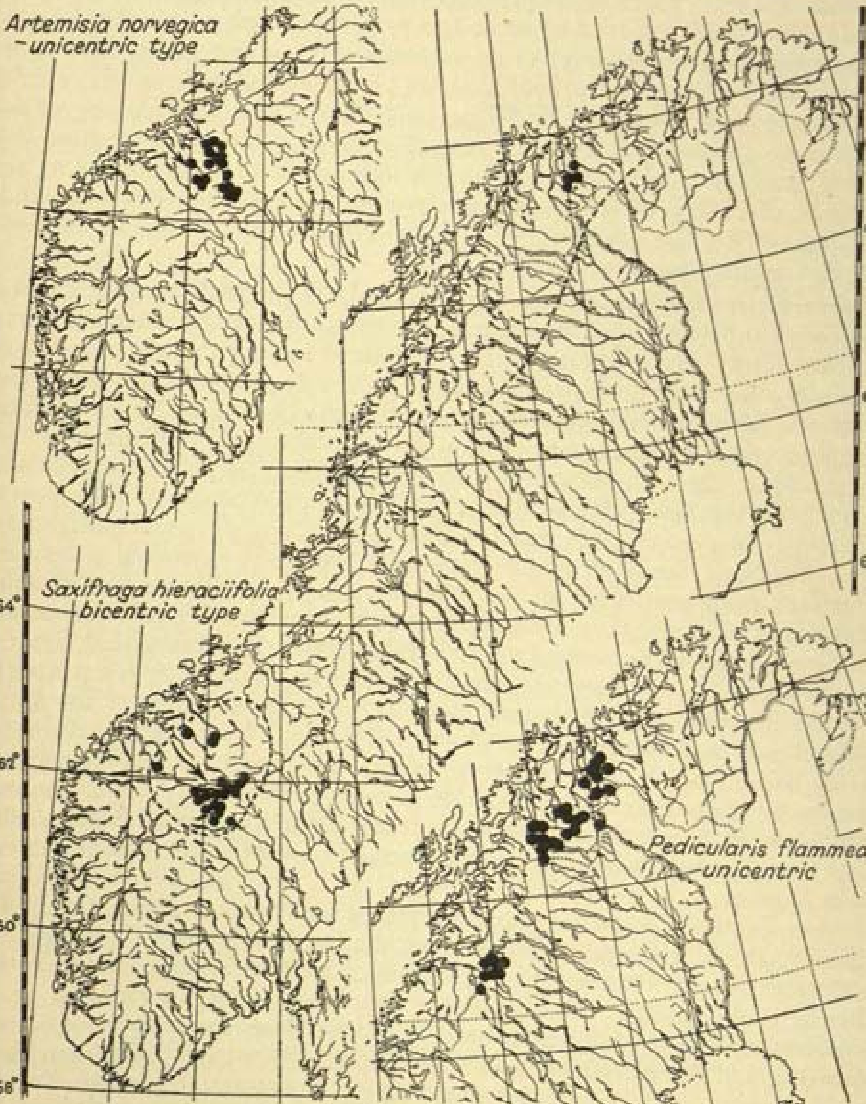

FIG. 194.—Map showing the distribution of a southern and a northern unicentric and a bicentric species in Fennoscandia. R. Nordhagen, *1201*, p. 12, fig. 5.

sought in the insects which are similarly distributed[515] and in the Norwegian lemming (see above). The Komsa and Fosna cultures (see p. 877), and a corresponding culture in west Sweden, were thought to indicate that the coast from Halland in the south to east Finnmark in the north was occupied by early (Aurignacian) man[516] who (isolated from the main palaeolithic territory

farther south) retained his palaeolithic stamp, although the sites themselves, as in north Fennoscandia, are later than the Portlandia transgression (see p. 1479).

Life according to this view survived in two different parts of the Norwegian coast and migrated postglacially from these refuges to the high mountains behind the coast. The position of the two sanctuaries is connected with the convexity of the coasts—the ice-streams from the interior were able to spread and break up into lobes[517]—or with the steepness of the coasts and the proximity to it of high mountains which served as nunataks.[518]

All this evidence, it is held, is only reconcilable with a survival of life during the last glaciation (or penultimate glaciation[519]) in asylums (*övervintrings-centra*), either *in situ* on nunataks and fells or on a coastal foreland—here diatoms may have survived[520]—which a lowering of sea-level by 100–125 m, as proved for Varanger,[521] converted into dry land.

The case for the survival of the alpine species is admittedly strong. For the rest it is less certain since disjunctions do not require survival for their explanation; there is no direct fossil evidence of the climate in west Norway at that time—the lowest spectra from Jaeren give a complete dominance of *Salix herbacea*[522] (80–90%); and the gap between the two centres of high mountains is one of a relatively oceanic climate where the ice broke up at the beginning of Finiglacial time (see p. 1523). Fossil material alone will provide absolute proof.

7. *North America*

Glacial epochs. The North American drifts, long deemed, e.g. by J. D. Dana, to be the product of one advance and one retreat, were afterwards and especially during the "eighties" of the last century ascribed to a First and Second glaciation. Early evidence of duality, gathered on the southern borders of the Keewatin and Labradorean ice-sheets in Wisconsin, Iowa, Illinois and Indiana or in the Mississippi basin, consisted of few and fragmentary layers of peat and the topographical contrast of the two drifts (see p. 898). As studies progressed, it became evident that the top drift in the extra-morainic region displayed numerous contrasts in the degree of erosion and weathering which were inconsistent with its reference to a single glaciation. Investigations led to the adoption of three, four or even five glacial epochs. Emphasis was laid on the importance of the weathered sands and gravels between the drifts,[523] and of gumbotil, which Iowan geologists deemed the supreme means of distinguishing the successive drifts.[524] Gumbotil is a grey to dark-coloured, sticky clay which breaks with starch-like or polyhedral forms when wet but is very hard and tenacious when dry. Its thoroughly leached, oxidised and non-laminated or stratified condition is a sign of prolonged weathering, though wind acting *pari passu* and extremely slowly may have played a part.[525] Indeed the gumbotils have often been regarded as loesses.[526]

For long, the succession was generally thought to consist of five glaciations (Nebraskan, Kansan, Illinoian, Iowan and Wisconsin), separated by four interglacials (Aftonian, Yarmouth, Sangamon and Peorian). The current classification of the glacial deposits in the Mississippi valley region, the standard succession in North America and possibly of the world—the Alpine glaciation in this respect suffers from being a mountain glaciation and the

north German glaciation because its drifts are thinner and less widely spaced, its weathered zones are less clayey and its outwash (with a northerly drainage) is less developed—is as follows:

Glaciations		*Interglacial Epochs*
4. Wisconsin	Mankato drift Cary drift Tazewell loess Tazewell drift Iowan loess Iowan drift	
		Sangamon
3. Illinoian (perhaps includes Iowan)		
		Yarmouth
2. Kansan		
		Aftonian
1. Nebraskan		

The glaciations were named from the States in which the deposits are well exposed. As introduced by Chamberlin[527] (Kansan, Wisconsin), Leverett[528] (Illinoian) and B. Shimek[529] (Nebraskan), they represent the earliest application of geographical names to the successive glacial stages. Chamberlin[530] and Leverett[531] created the interglacial terminology from type localities in the same region.

All five (counting the Iowan) glacial stages are represented in Iowa where many workers, including W. J. McGee, T. C. Chamberlin, F. Leverett and S. Calvin investigated the succession. Thorough studies have more recently shown[532] that the State was invaded five times by ice-margins and have mapped the several drifts.[533]

West of the Mississippi, the Nebraskan drift of the Iowan geologists[534] (this is equivalent to Chamberlin's Pre-Kansan and Subaftonian and probably to the Albertan of south-west Alberta[535] and the Jerseyan of the States east of the Alleghanies[536]) comes out from under the later drifts in east Nebraska and in south-west Iowa where it fills the preglacial valleys to a considerable thickness and is oxidised to a depth of 30–40 ft (9–12 m). This drift has been thought to emerge to become the surface drift in places in Missouri, Kansas and Wisconsin. Generally, however, and possibly always, it is hidden beneath the more extensive drift that followed it. A hard till in the Swan River, Manitoba,[537] may belong to this glaciation or to the succeeding Kansan.

The Kansan drift is much more extensive and continues from Iowa into the adjacent parts of Kansas and Missouri and into east Nebraska. West of the Mississippi and in Pennsylvania and New Jersey it was more widespread than the later drifts: in Illinois, Indiana and Ohio it was less so. Later streams have largely destroyed it, remnants of an average thickness of about 40 ft (*c.* 12 m) being preserved on narrow tabular divides occupying 10–30% of the original plain.[538] An old drift below the Illinoian drift of Illinois and Indiana which emerges from beneath the Wisconsin drift in Pennsylvania and New Jersey may also be Kansan.[539] The Nebraskan and Kansan drifts, though differing locally, are in general very similar in colour, texture and composition and in their state of weathering and erosion. In many places, they are only distinguishable by their relations to the interglacial soils, gumbotils and zones of weathering.

The Illinoian drift marks the maximum of the Labradorean ice in the

Mississippi basin though east of Ohio it appears to underlie later drifts. Leverett,[540] who first recognised the separate existence of this drift, traced its boundary through Illinois, where the drift is best developed and the Iowan is missing,[541] into Iowa and Missouri. It spreads on to the Kansan just as the later Iowan overlapped both the Illinoian and Kansan. The Illinoian ice flowed first into Illinois and south-east Iowa and later through Lake Michigan basin over east Illinois and west Indiana, its culmination in Ohio, Pennsylvania and New Jersey synchronising with its recession in west Illinois. A continuous moraine, lobate in outline and very prominent in some places (= Buffalo Hart Moraine), divides the drift into earlier and later substages.[542] In recent years the drift has been found west of the Mississippi River not merely in south-east Iowa but also in South Dakota and Minnesota.

The Iowan drift (the name was transferred from Iowa's most conspicuous drift to a thin drift later differentiated[543]) occurs west of the Driftless Area (see p. 727). It contrasts markedly with other drifts in its thinness, its distribution in interstream areas, its loess relationships, its burden of enormous and prominent granite erratics and in the sinuosities of its border.[544] The eastern boundary of the ice at this time is unknown—the Ronkonkoma-Cape Cod morainic system has been placed within it.[545] Doubts first raised by Leverett in 1909[546] as to whether enough evidence exists to warrant the continued existence of this glaciation and of the Peorian interglacial, admittedly the shortest of the American interglacial epochs,[547] have been expressed from time to time. The place and rank of the glaciation in the succession are in dispute, especially its relation to the Illinoian. Iowan geologists[548] have frequently stated the main evidence favouring its identity; the Loveland loess[549] is widespread between the Illinoian and Iowan drifts and the Iowan drift has no gumbotil but possesses a topography less altered than the Illinoian. Leverett,[550] however, denies the existence of a post-Illinoian and pre-Peorian loess and thinks conditions were not favourable to a gumbotil. He thinks, therefore, that the Iowan is the dying-out phase of the Illinoian glaciation (see below). Its separate existence is now generally rejected,[551] especially by those who are influenced by studies in Europe where only four glaciations are generally recognised (see above). It has been placed in the middle of an interglacial epoch,[552] Peorian being relegated to the rank of an interstadial, or interpreted as the Keewatin equivalent of the Labradorean drift.[553]

Recent research suggests that since no distinction can be drawn between the Peorian and Wisconsin (Tazewell) loess (outside the Wisconsin drift, the Iowan and Tazewell loess form the Peorian), the Iowan drift itself should be placed in the opening phase of the Wisconsin series,[554] a phase of the combined Cordilleran and Keewatin ice-sheets. This conclusion, which Leverett[555] accepted and has been adopted since 1943 by the United States Geological Survey, is strengthened by the fact that while the Iowan has one loess above it the Illinoian has two, and by the apparent agreement of the Iowan and Wisconsin drifts in their composition, texture and compactness: the Iowan drift was overlain by Peorian loess before it was leached and this loess in Illinois was in turn covered by "Early Wisconsin" drift before it was weathered. The combined glaciation has been styled the Eldoran[556] and subdivided in the standard region of the central United States into Iowan, Tazewell (= Early Wisconsin), Cary (= Middle Wisconsin) and Mankato[557] (= Late Wisconsin). In South Dakota and Iowa the four substages

of the Wisconsin are separated from each other by thin sheets of loess, the loess between the first and second and between the third and fourth being very thin and unweathered while that between the second and third is thicker and weathered. Hence the Iowan and Tazewell are closely related in time and the Cary and Mankato are a second closely related pair.[558] A very late Pleistocene loess, the Bignell loess, has recently been distinguished in Nebraska[559]: it is placed in the Mankato substage.

The Wisconsin drifts, distinguished by youthful topography and fresh, almost unweathered surfaces and by festooned end-moraines which reflect the great southern lobes of the ice, are naturally the most widespread at the surface, extending from the Pacific to the Atlantic, and to the Arctic islands of north Canada where the boundary, bordered by loess, is only imperfectly known.[560] They conceal most of the earlier drifts from Minnesota through eastern Dakota and eastwards into the Canadian provinces as well as over the Lake states, through New York and New England and over the glaciated area of Canada. Named by T. C. Chamberlin[561] in 1894 "East Wisconsin" and one year later "Wisconsin", they were divided into Early and Later Wisconsin phases[562] on the strength of slight differences in weathering, the channelled surface of the earlier drift, discordant moraines, and the occurrence of thin loess sheets and thin soils and peats between tills. Early, Middle and Wisconsin substages were later distinguished,[563] each marking a considerable advance following an intensifying of glacial conditions and the shifting that attended the greater nourishment of the ice on its western side. Subsequently, these readvances were named the Tazewell, Cary and Mankato substages, the Iowan being relegated to a first stage, or they were numbered simply first, second, third and fourth stages.[564] As both the Tazewell drift and its overlying loess are much thicker than the Iowan drift and loess, the Iowan advance may have been a relatively short-lived phase of a longer but less extensive maximum of Tazewell age. The Iowan was the Wisconsin maximum in South Dakota and Iowa but the Tazewell (Early Wisconsin, original Wisconsin) was the maximum in Indiana, Ohio and Illinois, e.g. the Green River Lobe.

The sequence of the lateglacial events was therefore as follows:

Mankato substage
  Two Creeks interval
Cary substage
  Brady interval
Tazewell substage

During the Brady interval,[565] the Tazewell ice receded at least 350 miles (*c.* 560 km) to beyond the Strait of Mackinac (between Lake Michigan and Lake Huron) and north of the Great Lakes; the drainage patterns and topography were altered and the Tazewell loess was weathered (Brady Soil).

Subsequently, a readvance of the ice of at least 275 miles (*c.* 440 km) carried the ice to its outermost limits in Wisconsin and into the states east of Lake Erie where it closed the drainage to form Lake Warren which discharged westwards. This Cary drift (of "Red ice"), which includes abundant end-moraines, many of them the product of readvances, e.g. the massive Valparaiso Moraine south of Lake Michigan, is most extensive in a broad belt spreading through Wisconsin, Michigan and north Ohio.

The withdrawal of the Cary ice along its whole front from the Atlantic (see below) to Minnesota and north of the Strait of Mackinac and the upper St. Lawrence allowed the waters in the Michigan and Huron basins to drain eastwards (Bowmanville low-water lake-phase) and uncovered probably the North Bay-Ottawa and Trent River outlets, thereby causing Lake Whittlesey

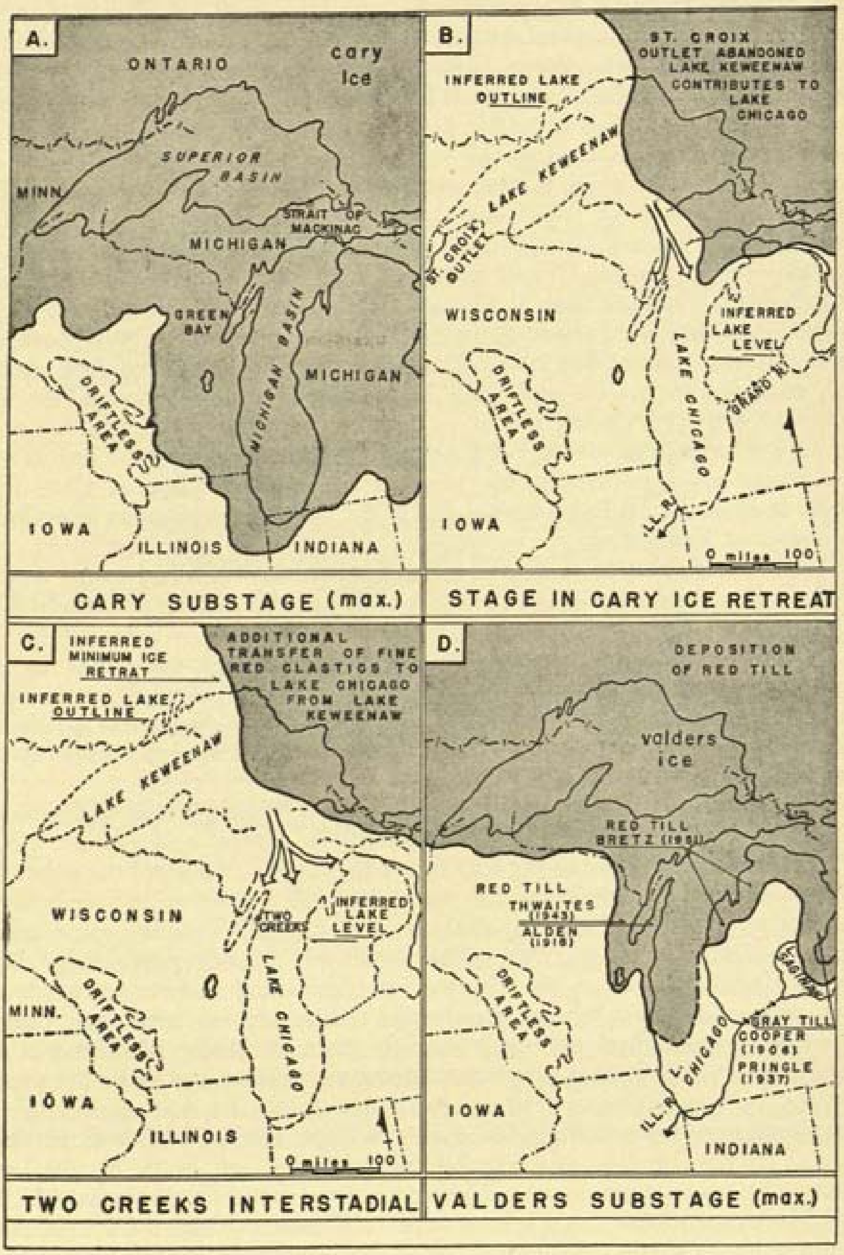

FIG. 195.—Diagrams showing the extent of the ice during the Cary and Valders substages and the Two Creeks interstadial. R. C. Murray, *A. J. S.* 251, 1953, p. 150, fig. 3.

to disappear, the sea to enter the lower St. Lawrence Valley (see p. 1309) and the lake in the Erie basin to discharge by the St. David's (now drift-filled) gorge which in its upper part was re-occupied by the River Niagara in Mankato time.

The Two Creeks Forest Bed[566] was formed during this withdrawal. The horizon probably extended from the type locality north of Milwaukee to near Port Stanley, Ontario, to 250 miles (*c.* 400 km) north of Toronto, and to 110 miles (*c.* 180 km) downstream from Montreal. The vegetation consisted of birch, hemlock, pine, spruce, fir and oak, with some elm, lime, beech and alder. This interval is represented by a subarctic forest in Wisconsin, by a low-water phase in the Lake Michigan basin (see p. 473) and possibly by marine beds, since covered by till in the St. Lawrence valley.

In early Mankato time, the ice south of Hudson Bay became dominant—"Patrician glaciation" (due possibly to a northerly shift of the Aleutian Low[567])—and moved more pronouncedly southwards so that it extended into regions east of central Ohio which had not previously been covered and simultaneously shrank back in Illinois, Indiana and south-west Ohio. This movement culminated south of the St. Lawrence and east of New York, the ice overriding mountains which in Early Wisconsin time had had local glaciers only and presenting a sea-wall along the coast and burying Anticosti.[568] The Mankato drift, which has numerous massive end-moraines, stretches from the Great Lakes region to the Adirondacks in New York and the Shickshock Mountains south of the St. Lawrence River—the ice stood at Glen Falls where it dammed up Lake Albany and at St. Johnsbury where it impounded Connecticut Valley Lake.

In late Mankato time, when the ice was prominent west and south-west of Hudson Bay, especially in Iowa and the Dakotas, the eastern ice barely filled the Ontario, Huron and Superior basins.

Current opinion holds that the Wisconsin glacial stage was a twofold one, the major break occurring in the Tazewell-Cary interval when, as we have seen, the Tazewell drift was eroded and the Tazewell loess was weathered (Brady Soil), though the Two Creeks Forest Bed (see above) belongs to the Cary-Mankato interval.

The approximate borders of the various drifts[569] (which will undoubtedly be modified when more fully investigated) in central and eastern North America are represented in the text-figure (fig. 196). Those of the substages of the Wisconsin glaciation (often marked by differences in the topography and drainage and in the strike of the end-moraines[570]) for the same region are given in fig. 235a, p. 1178. The Iowan was the maximum of the Wisconsin glaciation in Iowa, the Tazewell in Illinois and Indiana—this has not been recognised west of the Mississippi. The various substages, though doubtless present, had not until recently been definitely identified in the east,[571] where the relief is greater, the drifts are thinner and more permeable and the best evidence may be submerged beneath the sea. Nevertheless, they have now been distinguished in the Cape Cod area[572] and in other regions by the depth of leaching,[573] and in New York State.[574] In Long Island, the outer, Ronkonkoma Moraine is overlapped by the inner, Harbor Hill Moraine and this in turn by a later readvance. These outer moraines combine into a single moraine (of Iowan-Tazewell age ?) which crosses from Long Island to Staten Island. The three advances are also known from Cape Cod (see above) where the Ronkonkoma Moraine is represented in

Martha's Vineyard and Nantucket Islands. The Cary substage probably occurs at Boston, continues westwards to south of the Catskill Mountains and to near Oleon (east of Lake Erie) where it overlaps the Iowan-Tazewell drifts.

Two substages (Tazewell and Cary ?) have been discovered in the Catskill Mountains[575] and the various substages of the Wisconsin in South Dakota, western Iowa, south-west Minnesota and in various parts of Alaska.[576]

W. H. Hobbs,[577] in an aberrant and untenable view, has named the Nebraskan till of Iowa the Missourian and the Kansan the "Iowan", and has referred these and the later drifts of Iowa to ice issuing from the Adirondack-Catskill-Green Mountain highland. The various interglacial epochs (see

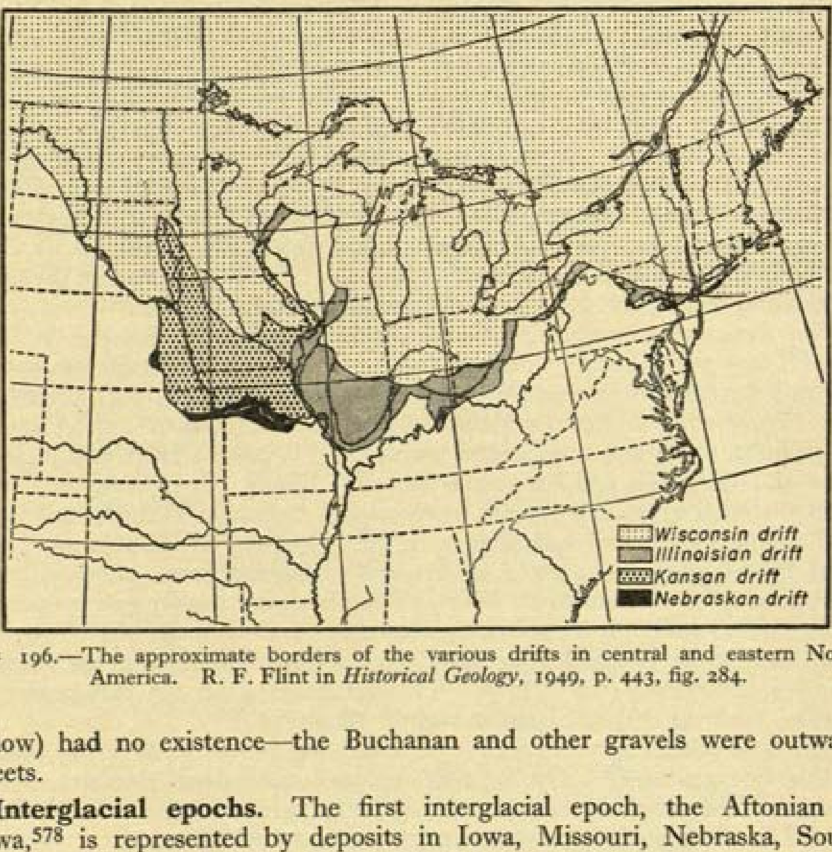

FIG. 196.—The approximate borders of the various drifts in central and eastern North America. R. F. Flint in *Historical Geology*, 1949, p. 443, fig. 284.

below) had no existence—the Buchanan and other gravels were outwash sheets.

Interglacial epochs. The first interglacial epoch, the Aftonian of Iowa,[578] is represented by deposits in Iowa, Missouri, Nebraska, South Dakota, Minnesota, Wisconsin and Illinois and was of long duration: valleys, 200 or even 400–600 ft (60 m or 120–180 m) deep, were cut during the interval.[579] It is characterised by widespread gumbotil of an average depth of 8–9 ft (2·5–3 m), by peats and deep soils, by loess and stream-laid material, and by land and freshwater molluscs[580] of species found in the local river-systems of to-day. Its climate[581] did not differ greatly from the present though studies of the mosses and other plants have led to the view that the climate was boreal or subarctic[582]—these, however, probably came from the end of the interglacial epoch. The plants[583] are pine, larch, spruce, fir, elm, oak, maple, poplar and balsam, and give a sequence with a middle term of oak between conifer horizons. The snails attest a rich land flora and the

mammals[584] include horse, bison, camel, elephant (*Elephas columbi*, *E. imperator*), *Mylodon harlani*, *Megalonyx leidei*, *Ursus americanus* and mastodonts which roamed over the plains into Texas and to the Gulf of Mexico, being found in Florida, Georgia, North Carolina and New Jersey. It is characterised by the association of *Gigantocamelus*, *Stegomastodon*, *Equus* and *Mammuthus*, *Nannippus*, *Rhynchotherium* and *Borophagus*. The gap between this Blancan fauna and the Hemphillian is now bridged in part by the Saw Rock Canyon fauna (Hibbard, 1952).

The Yarmouth interglacial, best known in eastern Iowa and south central Illinois, is 43 ft (13 m) thick at Yarmouth, Iowa, the type locality. To judge from the depth and perfection of the weathering profiles, it was of great duration and the longest American interglacial. *Lepus sylvaticus* and *Mephiticus mephitica* are the only animals it has yielded, though its plants, e.g. red cedar, oak, grasses and sedges, and its molluscs suggest a climate for part of the time at least somewhat colder than the present.[585] Beds in neighbouring States tentatively correlated with the Yarmouth interglacial—they overlie the Kansan till—bring the total number of species up to 124, of which 12 are plants, 92 molluscs and 20 vertebrates (of which 14 are extinct). They appear to indicate a warmer phase, not unlike tropical Mexico at present, with peccaries and tapirs, and a cool stage with hairy elephant, rabbit, skunk, deer and buffalo, and with pine, tamarack and juniper. The molluscs in the mid-continental region, e.g. Kansas, show a more equitable climate.[586]

The Sangamon interglacial, to which may belong the Rancho la Brea beds[587] (see p. 789) and the Saskatchewan Gravels[588] (south Saskatchewan has two interglacial horizons[589])—the name Sangamon was introduced by A. H. Worthen[590]—had an associated loess which extends over the Illinoian and Kansan drifts into unglaciated country and is named Loveland loess in Iowa and Nebraska and Sangamon loess in Illinois. It is associated with peats, diatomaceous earth, insects, molluscs and mammals,[591] the latter known in the main from caves and fissures in the Alleghany Mountains and from north Pennsylvania and north Alabama, and embracing horse, peccary, tapir, deer, antelope and sabre-tooth tiger. The plants are mainly gymnosperms, among which spruce is conspicuous; they seem to denote a colder climate[592] as do the insects[593] which are closely allied to (but not identical with) those found at Scarboro' (see below). The mammals from the Sangamon of Kansas, however, suggest warmer winters than now.[594]

The drift-filled valleys in the Finger Lakes region (see p. 283) may belong to this interglacial.[595] The animals included mastodont, elephant, horse, camel, beaver and sloth, though the "Aftonian fauna" of S. Calvin,[596] O. P. Hay[597] and B. Shimek[598] is apparently late-Pleistocene.[599]

Within the glaciated area, erosion has revealed interglacial beds round Lake Erie[600] and the Finger Lakes.[601] One of the most critical interglacial deposits in North America, and the first to be recognised,[602] is within this glaciated area at Toronto[603]; with that of Moose River (see below) it presents the most decisive evidence of deglaciation on that continent. Its beds continue as far as the Canadian shore of Lake Superior and Lake Ontario[604] (fig. 197). An interglacial successor of the "Laurentian River" (see p. 286) laid them down as a delta 190 ft (58 m) thick, 25 miles (*c.* 40 km) wide and 100 sq. miles (*c.* 260 sq. km) in area in a deeper "interglacial Lake Ontario", borings proving their existence along an old channel for 64 miles (*c.* 104 km). The muds lack lime and are charged with weathered mica flakes derived from

deep interglacial weathering. The surface of Lake Ontario was during the Don stage 60 ft (18 m) higher than now and during the Scarboro' stage 90 ft (27 m) higher, owing possibly to warping in the area of the Thousand Isle.[605]

The lower member, the Don beds, contains 41 species of freshwater mollusca, comprising 12 Unionidae and large Mississippi forms, and 38 species of trees which include paw-paw, red cedar and osage orange, as well as maple,

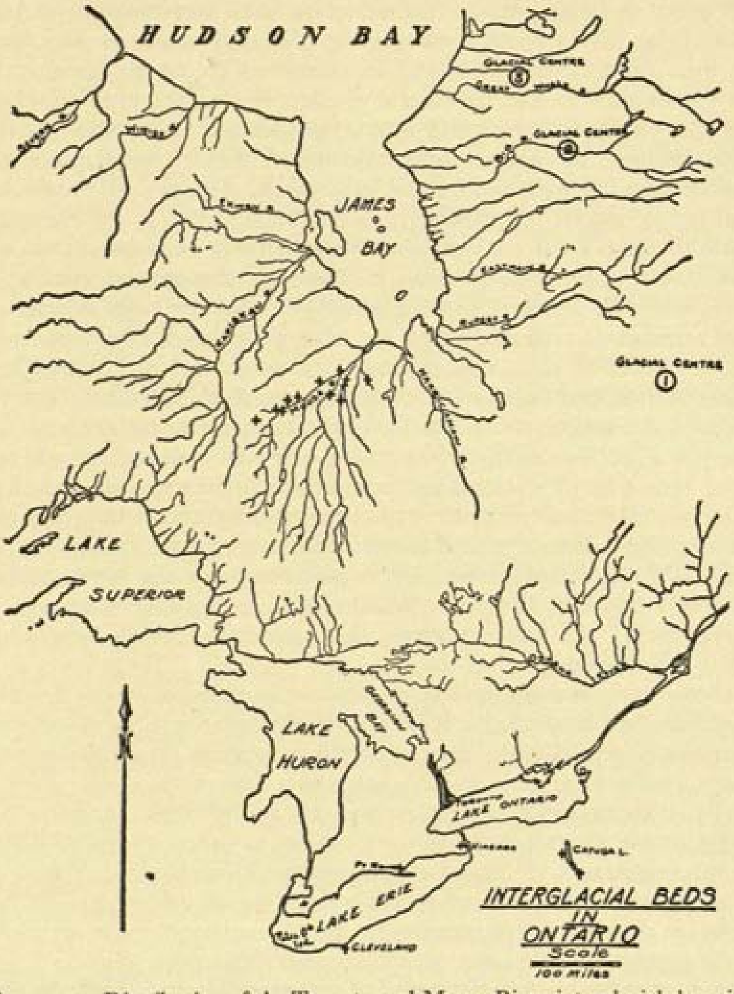

FIG. 197.—Distribution of the Toronto and Moose River interglacial deposits. A. P. Coleman, 299, p. 22.

ash, oak, hickory, elm, sycamore, beech, grape vine and three extinct species—pieces of charcoal give evidence of a forest fire. The land animals included ground hog, deer, buffalo, bear and giant beaver.

The overlying Scarboro' beds have 14 species of plants, with 31 genera and 72 species of insects, all but two of them extinct. Two of the extinct species occurred at Cleveland, Ohio, and suggest connexions with the south-west and the Mississippi.

The flora and fauna of the Don beds denote a climate[606] like that of Ohio or Pennsylvania and a temperature 4–5°C warmer. Ice even in the heart of Labrador is inconsistent with its organic life (see p. 917); seven of the trees do not naturally occur so far north and three of the unios are now missing from the St. Lawrence drainage and are confined to the Ohio and Mississippi valleys. The Scarboro' stage had a colder climate than the present: there were no Mississippi unios or warmer trees and the remains of willow, alder, blueberry and sedges may denote a climate like that of south Labrador, though all of them grow in boggy places farther south than Scarboro'.[607] A striated mammoth bone just beneath the overlying till suggests a final cold stage.

That this interglacial epoch was of considerable length is indicated not only by the organisms but by stream-erosion, by varve clays—E. Antevs[608] counted 586 varves—and by the slow epeirogenetic uplift which called the lake into being. Its age is uncertain since direct correlations through continuous sections with the distant interglacial deposits in the Mississippi basin cannot be made. Accordingly, it has been placed in the Sangamon,[609] Yarmouth[610] and even in the late Wisconsin.[611] Coleman, who has at different times referred it to each of the four interglacial epochs, finally equated it with the Yarmouth interglacial.[612] This early age is suggested by the great number of extinct species, namely 75–80 out of 180.

Peats, brown to black, compact, fissile and open textured, with silt, lignite and pieces of flattened stems and tree trunks, are distributed between two tills over an area extending 100 miles (*c.* 160 km) in an east–west and 50 miles (*c.* 80 km) in a meridional direction as shown by sections in the valleys which drain into James Bay,[613] including those of the Albany and Moose (fig. 197). Moss and wood associated with a boulder-pavement and two tills south of Nelson seemingly extend this Moose River interglacial horizon 450 miles (720 km) to the south-west.[614] Below the peat is a clay with molluscs of ponded water or quiet streams. Mammoth and mastodont are also known from these beds. In one exposure, the underlying till is weathered to a depth of 2 ft (*c.* 60 cm).

The climate was not unlike the present, as is evinced by the flora[615]; the tree trunks are not more than 5 ft (1·5 m) in diameter and the species are few. They consist principally of *Picea*, with pines next in importance as to-day, and *Carex*, *Salix*, *Equisetum* and *Hypnum* and *Sphagnum* moss. The pollen was chiefly of spruce with some pine and a very little birch and fir.

This relatively short epoch, whose relation to other interglacial horizons cannot be ascertained—it may be Sangamon or interstadial (see p. 917)—was closed by a glaciation which was heralded by an extraglacial lake. The advancing ice disturbed and removed some of the lacustrine clays, destroyed part of the interglacial deposits, and compressed the peat.

Evidence of three ice-advances and of an interglacial (?) Lake Agassiz (see p. 477) has been found, and an interglacial horizon with plants and fresh-water molluscs has been discovered in Manitoba.[616]

Eastern States. While each glaciation in the Mississippi basin, generally speaking, fell short of its predecessor so that older drifts emerge (fig. 196), in the New England States they were buried under later drifts as J. D. Dana[617] early recognised. For this reason, as well as because of the difficulties created by the greater relief, resistant rocks and coastal position, geologists who worked in the east held to the monoglacial view long after their colleagues farther west had abandoned it.

Although fossiliferous marine clays, with warm shells, beneath till had been early observed[618] and the complexities of the glacial succession in New England were recognised,[619] the first claim for plurality for the Atlantic strip was made in 1896[620] on the basis of the stratified marine clays of east Massachusetts, e.g. Boston, where drumlins rest upon them. The till of the Boston substage is overlain by the shelly clay of the Lexington substage with its drumlins.[621] Later workers[622] emphasised the glacial diversity from Maine to Pennsylvania, distinguishing the several drifts by erosion planes, by differences in composition, by degrees of weathering, and by palaeontological means. *Juniperus communis*, for example, has been found in glacial beds on Manhattan Island and marine warm-water species (sponges, diatoms, radiolaria) in till at Cape Cod, at Sankaty Head, Nantucket, and in the Gardiner's Clay of Long Island.[623] Although this evidence is perhaps not conclusive,[624] the full glacial sequence of the middle of the continent has been demanded,[625] e.g. for Long Island and the Cape Cod district which were the limit of the various glaciations. Jerseyan (Kansan), Illinoian and Wisconsin have been recognised in New Jersey[626] and in Pennsylvania.[627] The Watch Hill moraine of Rhode Island (Harbor Hill moraine of Long Island) differs markedly from the moraine of Cape Cod and Martha's Vineyard in its glacial topography and state of weathering.[628]

Nova Scotia had one or two glaciations.[629] Newfoundland, except for the Long Range, was overwhelmed during the Kansan or Jerseyan glaciations but was less severely and extensively glaciated during Wisconsin time when the invading ice reached a height of 1000 ft (300 m) and only local glaciers existed above this level.[630] The Magdalen Islands and south-east Labrador were not overridden by the last ice-sheet[631] and Baffin Land may have escaped this glaciation.[632] A relict flora, with endemic species, persisted, it is said, throughout the last glaciation on the Shickshock Mountains of Gaspé Peninsula, the Long Range of Newfoundland and the Torngat Mountains of Labrador (see p. 1392).

Interglacial submergence. Interglacial marine beds,[633] contemporaneous probably with those in the New England States (see above), with the Cape May Formation of New Jersey and the marine beds with warm shells of other Atlantic States[634] (see p. 1260), with the Toronto and Moose River deposits[635] (see p. 974) or the Sangamon interglacial,[636] have been found in the St. Lawrence and its tributary valleys in Quebec and east Ontario, e.g. at Montreal, up to 500 ft (150 m) A.S.L. on Newfoundland, on the adjoining coast of Labrador and on the Arctic coastal plain. This interglacial Champlain Sea, the equivalent doubtless of the Boreal Sea of the Old World (see p. 959), was warmer than the present sea since *Mytilus edulis* is often found and oysters lived at Montreal. Sugar maple, yellow birch, balsam and other poplars and 24 other plants grew on its shore. The sea had several species now extinct[637] and included crustacea, sponges, insects, shell-fish and a white whale. It inundated the plains about Hudson Bay and James Bay,[638] as marine shells in the uppermost till prove, and was deeper and more extensive than the lateglacial Champlain Sea. Ottawa Bay was 690 ft (210 m) above present sea-level to judge from an indefinite old shore and 510 ft (155 m) from actual marine shells.

Western States. In the Great Plains region (Dakotas to Alberta) only the Iowan, Tazewell and Cary substages are apparently developed[639] though the

Kansan has been claimed.[640] Farther west, the Cordilleran drifts have not yet been worked out. Notwithstanding statements to the contrary,[641] there seems to be indubitable proof of bipartition[642] (Admiralty and Vashon tills separated by a period of weathering and trenching of valleys and by Puyallup

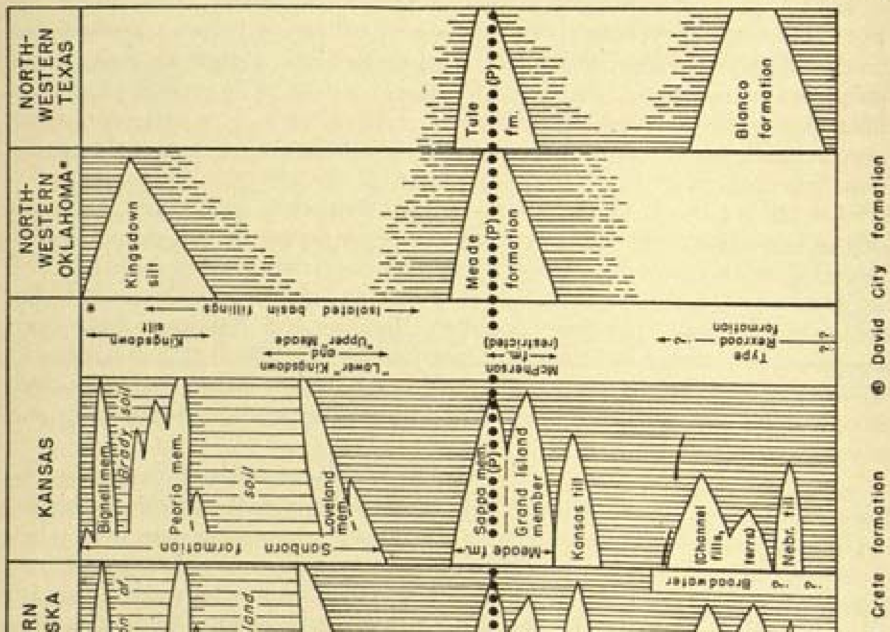

FIG. 198.—Classification and correlation of the stratigraphical units from the Mississippi valley to the central Great Plains. J. C. Frye *et al.*, *J. G.* 56, 1948, p. 520, fig. 3.

interglacial beds with plants and marine shells)—still earlier glacial deposits have recently been discovered on Vancouver Island.[643] This bipartition, first suggested by G. M. Dawson,[644] is established for Puget Sound, for the area of the Fraser delta, and for Vancouver.

A big oscillation, which may have been interglacial (Yarmouth), occurred in

Alaska[645]: the earliest drift, with its included stones, is thoroughly decomposed; the silts were deeply thawed and eroded and there were burrowing rodents; logs of trees occurred north of Port Nome, east of Point Barrow and on Herschel Island in the Beaufort Sea and in other places north of the present tree-limit; and the forests were an almost exact counterpart of those in south-east Alaska to-day—70% hemlock and 30% spruce indicate that the climax conditions had been fully attained as far inwards as the forest has been traced; trees were up to 25 m long and 1·5 m in diameter. Horses and antelopes lived in interglacial Alaska.

Corroborative evidence, like that from the Atlantic, has been procured from marine clays in California (see p. 916): it shows that there was floristically and faunistically a subtropical climate here during some phases of the Pleistocene.[646] Birds and mammals in this State point to the same conclusion.[647]

The Pleistocene deposits of the central Great Plains have been correlated by means of volcanic ash horizons, which provide good chronological markers, and by the associated mollusca[648] (fig. 198)—the eruption of Mount Mazama in Oregon, a chronological horizon of considerable importance, has been assigned dates ranging from 4000 to 15,000 years ago and by radiocarbon to about 6500 years ago.[649]

Conclusions. Reviewing the North American evidence, it seems that the continent experienced four glaciations with three interglacial epochs, one at least sufficiently long to be regarded as a time of complete deglaciation and to justify the view that the Ice Age in North America was bipartite with twin glaciations.[650] Not all four glaciations are known for each centre of radiation, though C. R. Keyes[651] has bracketed the various stages, some at present quite hypothetical, as follows:

Cordilleran ice-sheet	*Keewatin ice-sheet*	*Labradorean ice-sheet*
Vashan	Asawan	Wisconsin
Spokane	Iowan	Illinoian
Admiralty	Kansan	Indianan
Albertan	Adephian (= Nebraskan)	Jerseyan

In a scheme that has not found favour, each glaciation with its succeeding interglacial has been united into a cycle, the four cycles from below upwards being named the Grandian, Ottumwan, Centralian and Eldoran[652]: the terms are unnecessary and no reason exists for grouping the glacial and interglacial epochs in this way.

8. *Southern Hemisphere*

Very few interglacial deposits are known from South America.[653] Pumice, diatomite, peat and molluscs have, however, been found between drifts in Argentina and have been correlated with the great interglacial.[654] Outwash, moraines, loess and the double level of the lakes on the plateaux demonstrate a double glaciation for the Andes (see p. 923) though four glaciations, the equivalent of the classic Alpine four, have recently been claimed and named the Vallinamanca, Colorado, Diamante and Atuel.[655] South Georgia and East Africa had also a double glaciation (see p. 923).

The evidence from Australasia is meagre. New South Wales had a double

glaciation (see p. 923) and Tasmania had an ice-sheet phase (Malanna), a cirque-glacier phase (Yolande) and a mountain-tarn phase (Margaret) (see p. 921). An interglacial lignite in South Westland, New Zealand, contains spores of *Nothofagus* which indicate the proximity of beech forests.[656]

Antarctica has up to the present yielded no proof of an interglacial epoch. While such an epoch has been claimed for this region (see pp. 902, 918), it would appear at most to have been only a recession (see p. 679), though four glacial horizons have been discovered in the floor accumulations of Ross Sea (see p. 918).

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Chapter XXXVIII

PLEISTOCENE STRATIGRAPHY: BRITISH ISLES

Historical

In spite of their innumerable and perhaps unrivalled sections, natural and artificial, the British Isles have revealed little decisive evidence of interglacial epochs. Complications arise from the multiplicity of radiating and fluctuating ice-centres, from the relatively thin drifts, from the scanty fossiliferous deposits, and from the fact that much of the drift now lies on the sea-floor. The standard sequence is naturally provided by eastern England which is situated farthest from the ice-centres.

J. Geikie's claim for multiplicity, though supported by T. C. Chamberlin from North America and by Penck, Brückner and J. Partsch for the mainland of Europe (see ch. XXXVI), found little response in Britain. Geikie himself in his later publications insisted less on British and more on foreign evidence.

A double glaciation, the later one less extensive than the first and separated from it by the "great submergence", was a feature of most British writings of the middle of the last century (see p. 628). When the submergence was abandoned, much of the necessity for a belief in bipartition disappeared with it. Considerable weight was attached to the so-called "Middle Glacial Sands and Gravels" between a lower and an upper till. This tripartite succession, discovered in Lancashire and Cheshire,[1] including their coastal strips, was extended[2] to the Trent basin, eastern England, Cumberland and Westmorland, the Outer Hebrides and Ireland.

Many regarded the Middle Glacials as a means of synchronising the drifts of the various regions. They proved an oscillation, as in coastal Wales, the Lake District (Black Combe), the country south of Dublin and the Central Plain of Ireland, or even an interglacial epoch[3]: the beds contained evidence of erosion in the shape of clay-balls coated with sand and shell particles, peats, southern shells and occasional mammalian bones—mammoth has been found in them in several places in Cheshire.[4]

Others[5] however maintained that the Middle Glacials could not be so interpreted since they were not continuous over wide areas, had no constant relation to well-defined tills above and below, and had neither persistent features nor distinctive fossils. On the contrary, they were local and lenticular and inextricably interwoven with the till, and in the Vale of York and Cleveland Hills were true retreat moraines.[6] The so-called upper boulder-clay was lacustrine "book leaf" or laminated clay[7] (an observation likewise made for north Germany[8]) or was englacial debris liberated at the final melting (see p. 383).

Although this class of evidence is to be received with caution, since temporary oscillations or shifting subglacial streams may yield analogous features, especially in sections parallel with the stream or the ice-edge, later research has in the main but strengthened the interglacialist view. For instance, the Middle Glacials (= Corton Sands) of East Anglia (see p. 771) represent just such an oscillation between the North Sea Drift and the

Chalky Boulder-clay—the North Sea Ice may have completely withdrawn from Britain[9]—though it has been maintained that there was no interglacial epoch at this horizon.[10] They were laid down as deposits of a glacial submergence[11] or, as their heavy minerals indicate, as the outwash from the retreating North Sea Ice[12] or, more probably, of the advancing Chalky Boulder-clay ice.[13] Prolonged deglaciation followed: the Norwich Brickearth is thoroughly decalcified and oxidised[14]; Scandinavian and other erratics at the base, as at Ipswich and Cambridge (Traveller's Rest), are remnants of an older drift[15]; the East Anglian valleys, cut into the Norwich Brickearth in Norfolk, enclose the Middle Glacials and are themselves older than the Chalky Boulder-clay,[16] being wrapped over with it (they guided the flow of the ice which was buttressed upon and shattered, thrust and contorted their spurs of Crag and Chalk[17]); the Middle Glacials east of Cromer have been removed; and the direction of glaciation in North Sea Drift and Chalky Boulder-clay times differed markedly (see ch. XXXIII). The hiatus between the North Sea Drift and the Great Chalky Boulder-clay was a period of elevation and erosion, later of marine transgression.

The marine shells in these East Anglian Middle Glacials, contrary to an earlier view,[18] are indigenous[19] though they are undoubtedly of mixed origin and include fragile shells from the Crags. They have a northern aspect[20] (*Corbicula fluminalis* was apparently not then living in England[21]) though forms indicative of warm and cold conditions are found mixed together.[22] Satisfactory traces of the occupancy of the area by early man are scarce (see p. 1016)—possibly because the sands and gravels are porous and were deposited under great sheets of water, either fresh, brackish or salt.[23] Recently scrapers, points and racloirs of an industry termed Runtonian and allied to the early Clactonian have been discovered.[24]

1. Newer Drift

The Newer Drift is bounded by an end-moraine. This York Line runs from the north Norfolk coast to the mouth of the Shannon in western Ireland[25] (fig. 199). In the Vale of York it is formed by the York and Escrick moraines[26] which span the vale and consist of till interbedded with gravel and sand. Farther south it may include the Cromer Ridge[27] (see p. 772) and enclose the Brown Boulder-clay of Hunstanton (see p. 772) and less certainly the Upper Chalky Drift (see p. 771), e.g. of the Cambridge area, where fresh drift and eskers and strandlines and overflow valleys of glacier-lakes denote a recent glaciation (see p. 1189). It has, however, been stated that the ice at this stage on the east coast extended only to Flamborough Head or a little farther south.[28] Throughout its length, the moraine's markedly sinuous line is closely adapted to the relief, its loops being festooned over broad basins like the Vale of York and Cheshire Plain and the wider valleys which facilitated the ice-flow. It is curved backwards over the intervening uplands, e.g. the Cleveland Hills and the Galtee and Knockmealdown Mountains, which provided impediments.

Although an interglacial epoch preceding this drift has been denied[29] because there is no weathered layer with old soils or peats, it seems to be implied by the Middle Glacials of Lancashire and Cheshire, by the gravels in Holderness which contain warm fluviatile and marine molluscs (see below), by the isolated bones and teeth of land animals frequently found within the

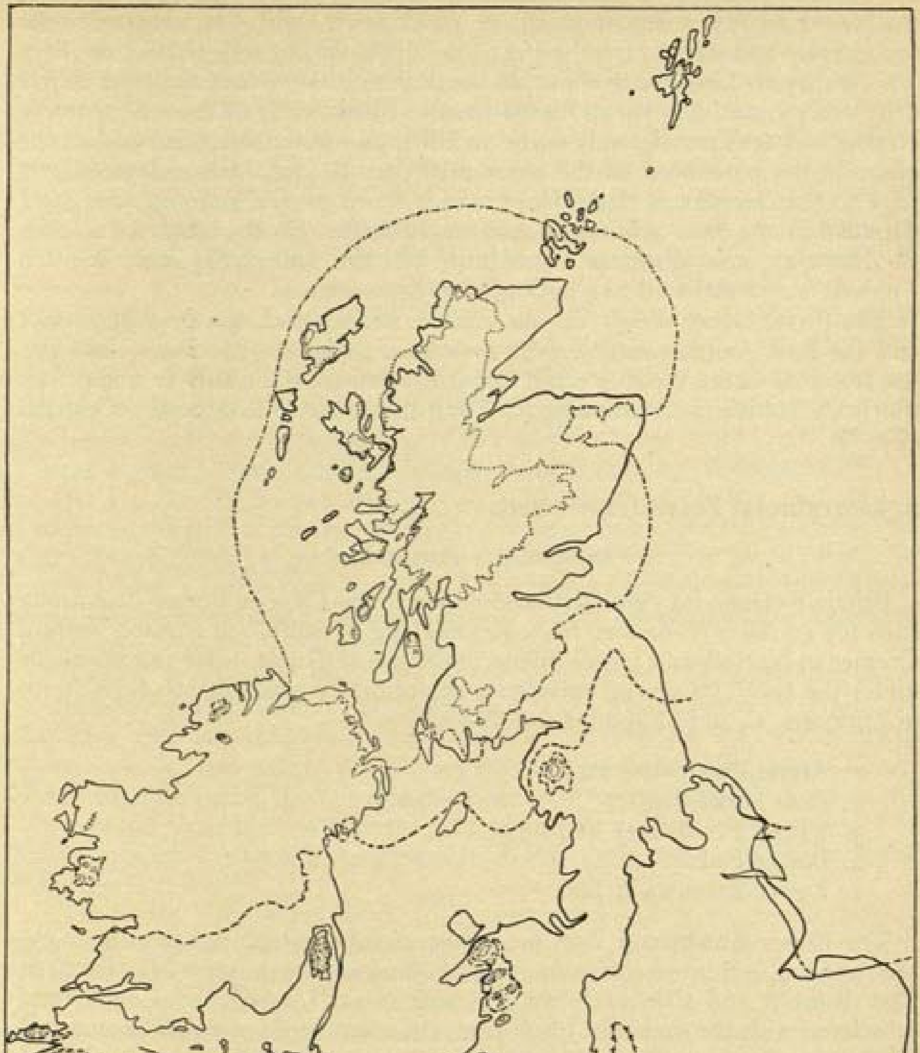

FIG. 199.—Limits of the older drifts (⊥ line), newer drift (York Line : continuous line) and main lateglacial stages—North British (dash line), Scottish (dot & dash line) and Highland or Moraine (dotted line)—in the British Isles. J. K. Charlesworth, *1876*, p. 923 fig. 23.

line of the moraine,[30] by the considerable dissection that took place before the Newer Drift was deposited, e.g. in Yorkshire,[31] and by the contrast in the topography and state of weathering of the drifts within and without the line. This is very strikingly seen about the south Pennines[32] where the fresh newer drift sweeps continuously up on the western flanks while on the east sporadic erratics and drift patches only occur on hill-tops, interstream areas and on the plain[33]—the patchiness of the older drift may be due to non-deposition[34] (due to the cleanliness of the ice) or, as is more generally thought, to later denudation of a once-continuous covering of drift. On the south the Chalky Boulder-clay, now dissected even down into the underlying rock, is often "piped" and weathered to a light grey or brown loam.

The (first) Great Welsh ice, the earliest Pennine ice, the Northern drift and the East Anglian earliest drift have been designated the Berrocian (Be), the (second) Great Welsh ice and Great Eastern ice the Catuvelaunian (Ca), the Irish Sea ice the Cornovian (Co) and the Little Welsh ice the Cymrian (Cy).[35]

2. Interglacial Fossiliferous Beds

(*a*) *Cromer Forest Bed*

Britain's classic interglacial accumulation is the Cromer Forest Bed which runs for 40 miles (*c.* 64 km) from Kessingland in Suffolk to Runton beyond Cromer in Norfolk and passes inland under the cliffs and drifts and outwards under the sea. Its several members, exceptionally totalling 100 ft (*c.* 30 m) in thickness, C. Reid classified as follows[36]:

5. Arctic Freshwater Bed
4. *Leda myalis* Bed
3. Upper Freshwater Bed
2. Forest Bed
1. Lower Freshwater Bed

The Lower Freshwater Bed, the lowest member which rests on the Weybourne Crag, is thin—2–5 ft (0·62–1·65 m)—and seldom preserved but between East Runton and Cromer forms a tenacious and carbonaceous river-mud associated with fish-remains, black peat, abundant seeds of marsh plants and bog bean, matted reeds and bracts of cotton-grass.

The laminated clays and current-bedded sands and gravels of the Forest Bed proper are in places 20 ft (6 m) thick and are estuarine and locally fluviatile and weathered into a soil (Rootlet Bed); they contain *Pholas*-bored cakes derived from the lower bed, occasional seams of mussels, and large quantities of driftwood with its bark stripped off in places and its roots severed, rounded or frayed. The surface is in places weathered into a soil. The vegetable matter,[37] comprising stools and boles of trees and remains of no less than 135 species of flowering plants, includes Scotch fir (first appearance in Europe), Norwegian spruce (the only tree species, as Lyell observed, not now indigenous in Britain), yew, maple, sloe, alder, oak, birch, hawthorn, elm, hornbeam, hazel, yellow and white water lilies, bogbean, hornwort and other pond weeds and willows, together with *Trapa natans*, *Ranunculus nemorosus*, *Hypecoum procumbens* and *Naias minor* which are not now native in the British Isles. Pollen analysis[38] shows that the Forest Bed was a mixed

oak forest which was impoverished towards the base where it was largely *Pinus* and *Betula* with *Ulmus*, *Salix* and *Picea*. *Abies* was absent. The succession is an interglacial one, minus the lowest and uppermost horizons.

The associated mammals[39] included the monkey *Macacus*[40] (previously found at Grays, Thames valley[41]), *Elephas meridionalis*, *E. antiquus* (denied[42]), *E. trogontherii*,[43] *Dicerorhinus etruscus*, *Diceros merckii*, *Hyaena striata*,[44] *Hippopotamus amphibius*, *Ursus spelaeus* (= *U. deningeri*[45]), *U. arvernensis* (denied[46]), *U. savini* (common bear of this bed and possible ancestor of *U. spelaeus*[47]), numerous species and individuals of deer[48] (*Cervus sedgwicki*, *C. cervicornis*, *C. cornutorum*, *C. polignacus*, *C. elephas*, *C. capreolus*, *C. megaceros*—*C. dama* was not present[49]), *Machairodus latidens*, 16 rodents including *Trogontherium cuvieri* and *Castor fiber*,[50] 6 insectivors,[51] *Equus robustus*,[52] and such vertebrates as walrus, spermwhale and fish.[53] They also included a cold element which embraced *Felis spelaea*, *Ursus spelaeus* (see above), *Elephas primigenius*[54] (denied[55]), *Gulo luscus* and *Ovibos moschatus*,[56] the last named thought to have been derived from some other bed[57] or, with *Cervus megaceros* and *Rangifer tarandus*, to be doubtfully determined.[58]

The Upper Freshwater Bed lies in hollows on an eroded and deeply weathered surface of the Forest Bed. Its lacustrine clays are full of marsh plants (water lilies, sedges and aquatic docks), bones of fish, birds, amphibia, reptiles and a microtine fauna,[59] with freshwater molluscs that include *Corbicula fluminalis* and several species, either extinct or like *Hydrobia margarita* no longer living in Britain.

The *Leda myalis* Bed of fine, current-bedded loamy sand, 20 ft (6 m) thick, is characterised by *Yoldia* (*Leda*) *myalis*. This arctic species, unknown in the Crag, occurs like the associated shells in the position of life with valves united. Reid and others placed this marine bed below the Arctic Freshwater Bed: Solomon reverses the position. Its fossils resemble those of the Weybourne Crag but its mineral grains, similar to those of the North Sea Drift, indicate the arrival of detritus from the north and the advance of the Scandinavian ice.[60]

The Arctic Freshwater Bed, an ancient land-surface, is found impersistently as at Mundesley, Beeston, Ostend and near Bacton on the north Norfolk coast. Its fine, current-bedded sands and loams, 1–4 ft thick, contain freshwater shells (*Succinea putris*, *S. oblonga*, *Valvata piscinalis* and *Pisidium henstowianum*), and its laminated peaty loams and clays, lenticular in form, were deposited in channels as a flood loam. It has arctic birches, alder and willow (*Salix polaris* and *Betula nana* first appear here in Britain) and mosses inclusive of the boreal *Hypnum turgescens* (now abundant in Spitsbergen, Greenland, Bear Island and north Scandinavia). The rodent *Citellus* has also been found. The arctic conditions are confirmed by seals, whales and walrus and by the lack of trees. The temperature was probably 11·1°C lower than now.[61]

While the Lower Freshwater and Arctic Freshwater Bed, the two limiting members of the Forest Bed Series, are *in situ* and arctic in character, the Forest Bed itself is a mixture of species of different ages and climates.[62] The fish, amphibia, reptiles and birds are generally modern species; the mammalia include warm species which survived from the Crags, many or all of them extinct (all the 63 species of terrestrial mammals may be extinct[63]), and tundra and northern forest types, such as the musk ox and glutton. The marine mollusca register a temperature as cold as that of the Weybourne

Crag[64] though the freshwater shells, as one might judge from their source, have a more southerly aspect.

This mixture has caused the age of the Forest Bed to be disputed. Yet it is generally believed[65] that the warmer element, comprising some upper Pliocene species, was carried northwards from a warmer biological province or some older beds by a north-flowing river (usually identified with the Rhine but more probably the combined Lys, Scheldt and Meuse[66]) which transported blocks and minerals from the south.[67] The climate, as the trees attest, was at least as warm as present-day Norfolk. The flora and alluvial plains with lakes and sluggish rivers resembled those of the Norfolk Broads of to-day.[68]

To the age of the Forest Bed may be referred the Cromerian fauna found at 60 ft (*c.* 18 m) O.D. near Harwich, Essex,[69] the bottom layer in Kent's Cavern with *Machairodus* and the Cromerian *Pitymys gregaloides*,[70] and the Castle Eden flora of the freshwater clays in fissures in the Magnesian Limestone of Co. Durham: the clays contain molluscs, ostracods, tree trunks, mosses, seeds (suggesting early Reuverian), bones of fish and a few mammals including *Elephas meridionalis*.[71]

(*b*) *Lake-sites*

Among other British beds, presumably interglacial, are certain lake-sites which, like other interglacial occurrences, are little more than "lucky dips" into a past which is largely obliterated. One of the most important of these is at Hoxne, about midway between Norwich and Ipswich. Here, a silted-up lake or river-channel presents the following succession[72] (fig. 200):

8. Boulder-clay or solifluxion trail, 2 m thick (= Upper Chalky Boulder-clay); middle to late Mousterian.
7. Vaminated clays, *c.* 2·5 m thick, with peat at the base and bones of horse, red deer, beaver and elephant, temperate molluscs, alder with Scotch pine, spruce, oak, birch, elm and hazel; Clactonian III ("Early Mousterian").
6. Gravel, 1–1·5 m thick, with bones of mammoth and reindeer; upper Acheulian.
5. Blackish brickearth, 6–7 m thick, with arctic willow, dwarf birch and leaves and mosses of arctic type.
4. Peat with abundant mosses and temperate plants.
3. Greenish-grey brickearth with temperate plants and molluscs.
2. Great Chalky Boulder-clay (?), 7·5 m thick.
1. Glacial sand (Corton Sands?).

Woldstedt[73] interprets the succession to indicate the North Sea glaciation (= Chalky Boulder-clay), followed by two interglacial horizons (Elster-Saale, Saale-Weichsel) and capped by a solifluxion layer (No. 8). The mammoth, reindeer and arctic plants denote a true glacial period (Saale) and not merely the cold horizon of Skaerumhede (see p. 950). Recent evidence, however, seems to prove that there is only one warm bed (Mindel-Riss) with a true boulder-clay above (West, 1954).

A somewhat similar succession has been found at two other "buried lake-sites", namely at Foxhall Road (Derby Road), Ipswich,[74] and at High Lodge (2½ miles north-east of Mildenhall), Suffolk.[75] The temperate bed at Ipswich

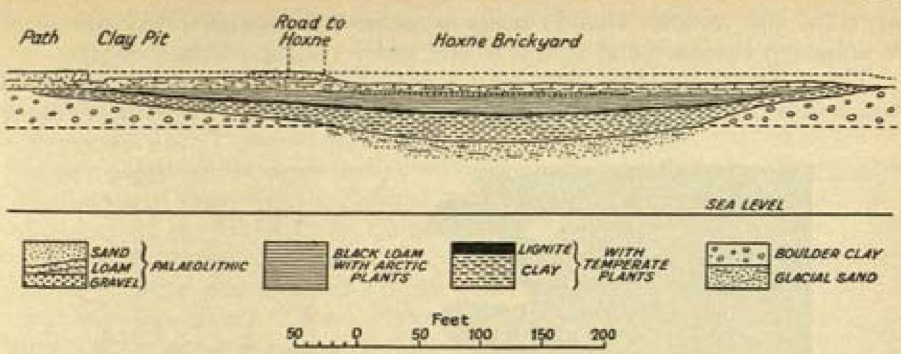

FIG. 200.—Section through the Hoxne brickyard. *Mem. Geol. Surv. Brit. Reg. Geol.*, "East Anglia", 1937, p. 58.

contains lower Acheulian implements while at High Lodge gravels and brick-earths between Great Chalky Boulder-clay below and trail (Upper Chalky Drift) above have yielded evolved Clactonian, Acheulian and Levalloisian industries.

These lake-sites, which together may provide equivalents of the Mindel-Riss interglacial of the Somme, viz. early Clactonian, early and middle Acheulian and early Levalloisian, show that the climatic conditions in south Britain at that time were generally similar to those of the present but perhaps with more forest of alder, oak, birch, pine, hazel and spruce.

(*c*) *River-terraces*

High-level gravels of varied composition and some antiquity are widespread through southern England. In Berkshire and Oxfordshire and other counties margining the London Basin, they form a quartzose or (Bunter) quartzite gravel[76] which is probably Tertiary though modified by ice. On the Chiltern plateau,[77] where they occur at a fairly uniform altitude of *c.* 400 ft (120 m) on flat-topped hills and in genetic relation with these, they consist of local or neighbouring material, e.g. Lower Greensand, Chalk and Tertiary, with far-travelled detritus, such as Carboniferous Limestone, Bunter pebbles, Lias fossils and Red Chalk, referable to marine action.

The gravels belong to various Tertiary ages, including the Lenham Beds,[78] and in north Middlesex, Hertfordshire and Essex include the deposits of a Proto-Thames[79] which flowed north of its present course and through the Vale of St. Albans to Hertford, Ware and Chelmsford. It received tributaries from the Weald which deposited pebble gravels, consisting of local material, e.g. cherts, and possibly representing the fluviatile equivalents of the Westleton Shingle[80] (see pp. 766, 771). Glacial redistribution is shown by disturbances in the underlying strata,[81] by included palaeoliths[82] and by foreign constituents which in part represent the outwash fans of an ice-sheet[83] older than that which laid down the Great Chalky Boulder-clay. These deposits of an earlier Thames, which continue upward in elevation and backward in time the record of the recognised Thames terraces (see below), include the Winter Hill Terrace and the lower Black Park Terrace and the still earlier Higher and Lower (Harefield) gravel-trains[84] (fig. 201). The Triassic debris entered the Thames valley by Goring Gap and was redistributed by ice from the pre-existing river-gravels.[85] Thus the Winter Hill

drifts of the middle Thames are represented downstream by gravels of Wimbledon Common and Kingston Hill which contain Triassic debris.

The corresponding high-level gravels of Cretaceous and Tertiary fragments which lie south of the ice in Hampshire[86] were laid down by Tertiary rivers or

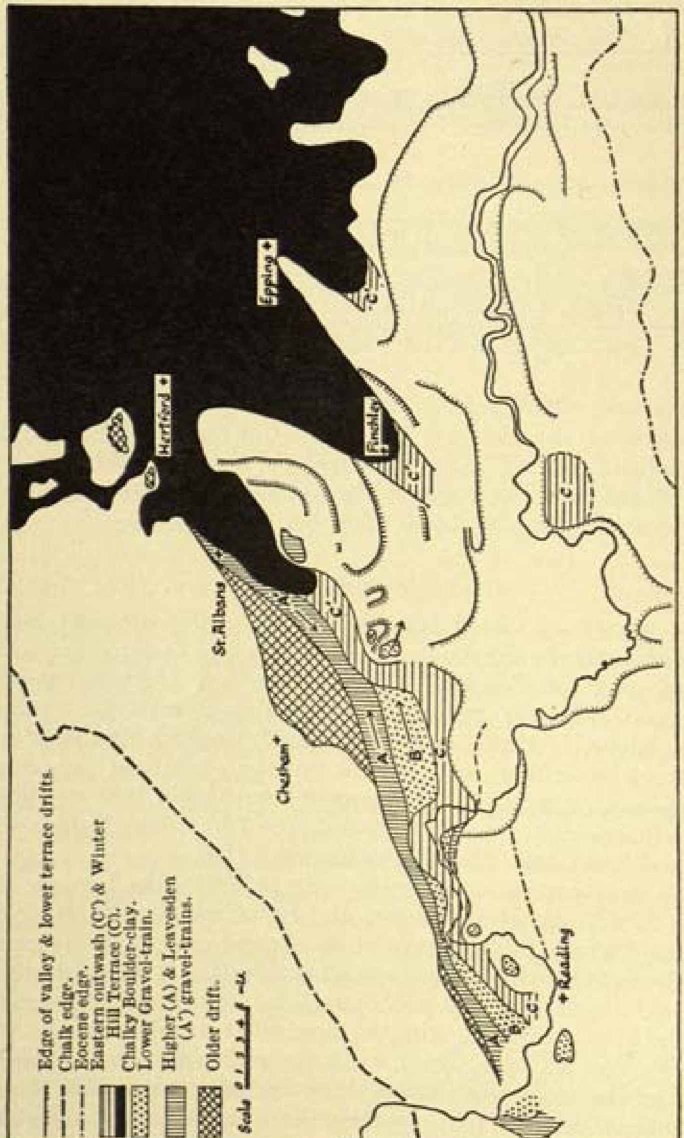

FIG. 201.—The Chalky Boulder-clay and the course and subdivisions of the earliest deposits of the Thames west of London. S. W. Wooldridge, *Q. J.* 94, 1938, p. 657, fig. 7.

seas; they remained undisturbed except for floods from melting snows (see p. 1082).

Thames terraces. The Thames terraces,[87] the northernmost terraces in eastern England—there are for example no terraces between the Thames and Wash—build sheets and isolated patches of which the thickest, most extensive

and most fossiliferous lie north of the valley and below London. Their gravels and beds of sand, frequently capped by loam or brickearth, represent the waste of Cretaceous and Tertiary rocks and older plateau gravels[88] (see p. 1215). While petrologically they do not differ notably according to horizon, their composition varies with the drainage area. Thus the gravels on the south contain only local material, e.g. flint, Lower Greensand chert, Folkestone ironstone and Bagshot Sand, and on the north, Carboniferous, Jurassic and Cretaceous material. The bulk is angular chalk, flint, white quartz, slate and quarztite.[89] The brickearth, mainly associated with the last stages of the Middle or later terraces, is of composite origin. Though ascribed to deposition in the sea[90] or in a lake ponded by ice in the North Sea,[91] it was probably formed by wind-drift under drier conditions (see p. 530), by tranquil inundation along river-margins[92]—it encloses numerous species of freshwater and terrestrial molluscs—or by subaerial waste at the foot of slopes.[93] Thus many skeletons of lemmings were discovered "rolled up as though they had been smothered while hibernating in burrows".[94]

These terraces, early thought to be marine beaches,[95] were later attributed to deposition along the sides of stagnant ice[96] and in part to fluvioglacial streams.[97] While the latter undoubtedly contributed their share, the terraces are in the main of fluviatile origin as J. Morris[98] first pointed out. Thus each terrace varies in height with the fall of the valley, to a slight degree longitudinally, much more transversely—the intervals between the terraces diminish upstream.[99] Prestwich distinguished high-level and low-level terraces and Whitaker[100] recognised three terraces, denoted first, second and third or alternatively high, middle and low. This division was afterwards modified,[101] by the addition of a still earlier terrace, into First, Second or High, Third or Middle, and Fourth or Low Terrace[102] (fig. 202).

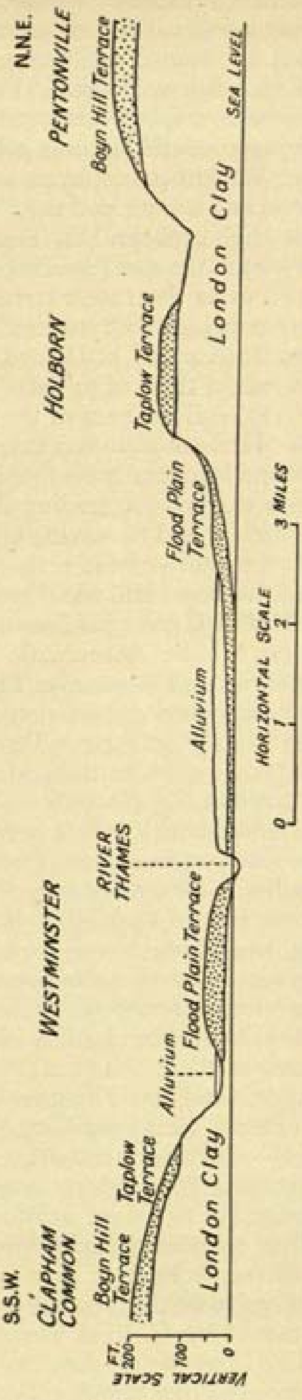

Fig. 202.—Transverse section across the Thames valley, with the river-terraces. *Geol. Surv. Mem. Brit. Reg. Geol.*, "London and Thames Valley", Ed. 2, 1947, p. 56, fig. 19.

The First or Dartford Heath Terrace which occurs at 130 ft (*c.* 40 m) or more is now markedly fragmentary on the south side (Dartford Heath,

Shooter's Hill, Crystal Palace, Hangar Hill, Wimbledon, Kingston Hill and Swanscombe). The Swanscombe series consists of 30 ft (9 m) of gravels divided by loams into Lower, Middle and Upper beds, the first with Clactonian flakes, the second and third with Acheulian: it contains erratics of southern origin (Cretaceous and Tertiary), together with erratics from western sources[103] (Bunter pebbles, Upper Carboniferous grits, Lickey Hill arkose, Wrekin granophyre, and rhyolite, basalt and tuffs from the Welsh borders) and has yielded the Swanscombe (female) skull (see p. 857).

The High or Boyn Hill Terrace,[104] which about London and for 50 miles (*c.* 80 km) to the east (Swanscombe) approximates to 100 ft (*c.* 30 m), is often referred to as the 100-ft terrace. It naturally rises upstream—at Maidenhead (near which the type localities of Boyn Hill and Taplow are to be found), it is 140 ft (*c.* 43 m), at Oxford, 240 ft (*c.* 73 m)—and falls downstream: from the mouth of the Lea to Swanscombe the gradient is less than 3 in. per mile (1:21,120) and the neck of the estuary was probably only 15 miles (*c.* 25 km) away. Its flood plain was at least 6 miles (*c.* 10 km) broad, between Dartford Heath and Romford even 12 miles (*c.* 20 km)[105]; the river continuously carved out new channels, aggrading them and abandoning them, so that the gravels are lenticular and of varying texture. In reality there are two terraces or two ledges cut into the solid rock over which the gravel sweeps down. They are named the Boyn Hill and Furze Platt terraces,[106] the latter, the equivalent of the "Middle Gravel" of Swanscombe and containing Grays Inn Lane palaeoliths (= Middle Acheulian), and the Boyn Hill terrace with "derived" Abbevillean and Clactonian implements. The combined terrace represents an imposing total aggradation of an extremely long interglacial epoch.

The Middle or Taplow Terrace,[107] ranging between 46 ft (14 m) and 60 ft (18 m) and known as the 50-ft terrace, is widely distributed; it extends from west London, e.g. Shepherd's Bush and Staines, to Ilford in Essex and Erith and Dartford in Kent: it graded with a sea at this height but descends to below sea-level from Erith eastwards.[108] This terrace is divisible into two,[109] an earlier No. 1 with early Levallois implements (also termed the Upper Taplow, Iver or Lynch Hill Terrace[110]) which was formed during a tundra phase, and a later No. 2, with middle Levallois implements, the two terraces being separated by an important solifluxion horizon correlated on archaeological evidence with the Main Coombe Rock of Northfleet.

The Upper Flood Plain Terrace[111] (Ponders End stage), which about Windsor is about 6 ft (2 m) above the present flood plain, at Chertsey about 10 ft (3 m) and near Hampton about 20 ft (6 m) above the flood plain, graded with a 25-ft (8 m) sea-level. The Lower Flood Plain Terrace or Halling stage,[112] which is intermediate between the Upper Flood Plain Terrace and the modern flood plain, may belong to the first interstadial of the last glaciation.[113]

These terraces are important: they chronicle the sequence of changes of climate (see below), of mammalian life[114] (fish have also been obtained[115]), and of palaeolithic cultures[116]—the 200-ft (*c.* 60 m) or Ambersham Terrace was named by C. Reid the "Eolithic Terrace". The climate deteriorated steadily from the highest to the lowest terrace. The highest terrace at Swanscombe has yielded *Diceros megarhinus*, *D. leptorhinus*, *Equus* sp. cf. *stenonis*, *Trogontherium cuvieri*—the bones as elsewhere in the terraces are seldom much rolled or broken and were entombed on the spot as Morris[117] averred.

The Taplow Terrace is overlain by glacial coombe rock and an upper brickearth sealing floors containing unrolled middle Mousterian implements, as at Acton, Crayford and Northfleet. It shows the ousting of the warmer species, associated with the sensitive ivy and poplar,[118] Chellean implements[119] and rolled Acheulian and Levalloisian of the lower gravels, by colder species and the coming in, during the Crayford stage, of cold animals, e.g. glutton, musk ox (?), reindeer, mammoth, woolly rhinoceros, arctic and Scandinavian lemmings and northern voles. *Corbicula fluminalis* and the leptorhine rhinoceros disappeared from the Thames valley in the Crayford stage of this terrace, hippopotamus in the early Middle Terrace at Grays. Disturbances were created by drift-ice,[120] and an occasional boulder was ice-borne.[121] The worsening climate culminated in the Flood Plain Terrace whose arctic mammalia comprise mammoth, woolly rhinoceros and abundant reindeer, e.g. at Stoke Newington[122] and Admiralty Buildings.[123] This is the "reindeer period" as S. V. Wood[124] noted.

Non-marine mollusca,[125] found mainly in brickearths (whose composition and more tranquil accumulation favoured the collection and preservation of even the most fragile shells) confirm this climatic tendency in so far as they betray any variation. *Corbicula fluminalis, Unio littoralis* and other warm shells become smaller and fewer through the terrace-sequence and disappear during the Taplow's closing phases; *Theodoxus cantanus, Belgrandia marginata, Viviparus diluvianus, Lymnium cantanius* and *Sphaericum solidum* had disappeared earlier.

The maximum cold succeeded the lowering of sea-level following the Taplow Terrace. This is witnessed by the *Betula nana* at Admiralty Arch, the arctic vegetation at Admiralty Buildings, and especially by the Ponders End Beds in Essex.[126] These dark clays, later than or an integral part of the Flood Plain Terrace, extend at an average of 17 ft (5 m) below the present marsh along the valley of the Lea from Ponders End to Stratford. Their molluscs, which include such boreal species as *Columella columella, Planorbis arcticus, Vertigo parcedentata, Janinia muscorum* var. *lindstroemi* and dwarfed individuals of species having a wider distribution, signify a July temperature of 10°C or that of south Iceland or Lapland to-day; their mammalia[127] include mammoth, woolly rhinoceros and *Dicrostonyx tenseli*; and their flora,[128] bearing the impress of the climate of north Lapland, consists of a matted debris of *Betula nana* and *Salix herbacea* and of mosses which are now either extinct in Britain or confined to the highest summits of Scotland. Disturbances by solifluxion and river-ice and scratches on a mammoth's tooth also testify to arctic conditions. These persisted throughout the Thames basin at this time since similar cold molluscs occur at Lewisham,[129] the Flood Plain Terrace passes into trail (see p. 1080), and river-ice occasioned minor faulting.[130] The Thames had then probably a smaller volume since the springs froze most of the year and its floor was occupied locally by marsh which in winter was buried beneath snow.

The terraces likewise record the habitation of the valley by successive races of man. Abbevillean and Acheulian (Clactonian I and II) implements have been extracted from the Winter Hill terrace between Caversham and Henley[131] and the highest terrace at Swanscombe.[132] Clactonian IIa and middle Acheulian from the Barnfield Pit (= Boyn Hill terrace), from the middle gravels at Swanscombe, and from the Furze Platt gravels[133] near Maidenhead; broken and abraded Clactonian and Abbevillean from Dartford Heath

gravels[134]; late Acheulian and early Mousterian or middle Levalloisian from Baker's Hole near Ebbsfleet[135] and from the later part of the Taplow Terrace, with working floors at Acton, Stoke Newington and over much of north-east London—late Acheulian also occurs from the last interglacial horizon in the brickearths of Elvedon in Breckland and in the Chiltern Hills; middle Mousterian from above the Coombe Rock; Solutrean from the Flood Plain Terrace at Admiralty Buildings, Whitehall; middle Aurignacian or Creswellian (?) from the Halling stage[136]; and Magdalenian (= late Levalloisian[137]) from the Ponders End Beds (below the plant beds) and the Flood Plain Terrace at Uxbridge and a few other places.[138]

The relation of the terraces to the glacial succession north of the Thames has been much disputed. The Kingston Leaf and Boyn Hill benches, which correspond to two low sea-levels and thus to two cold phases, were cut into the 200-ft (60 m) platform before the ice arrived in Essex[139]—the later of the two was contemporaneous with the glaciation of the Hornchurch section (see below).

The ice of the Great Chalky Boulder-clay stopped short of the valley and sent tongues down the northern tributaries, e.g. the Crouch to the estuary, the Lea to Chingford and Finchley, the Brent to Hendon, the Coln to Watford. This boulder-clay was deposited on the Ambersham Terrace (190 ft: 58 m) and in the little valleys that had been cut into it[140] and passes beneath the Boyn Hill Terrace[141] at Hornchurch, Upminster and East Rumford which seemingly contained only Bunter-Jurassic material without any Scandinavian, Scottish or north English erratics[142] (see p. 774). This relationship suggests that the Thames terraces are later than this glaciation[143] in agreement with the early view that the Thames terraces were "postglacial",[144] and with the deposition of a coombe-rock between the Dartford Heath and the 100-ft (30 m) terrace gravels. It agrees also with the igneous erratics in the terraces,[145] including fragments from the Midland Valley of Scotland (the Boyn Hill Terrace is at least in places merely redistributed glacial outwash[146]); with the outwash gravels, contemporaneous with the highest terrace at Crozley Green[147]; and with the Levallois implements in the gravels overlying boulder-clay near Southend.[148] That cold conditions preceded the gravels of Dartford Heath and Swanscombe[149] is proved by the inclusion of *Gryphaea* shells, derived from the Jurassic facies of the Great Chalky Boulder-clay, of numerous pebbles of metamorphic and igneous rocks (including two of Cheviot origin), and of glaciated boulders and striated palaeoliths. These undoubted derivatives from a till of Chalky-Jurassic facies may represent the glacial phase which made the North Sea Drift of East Anglia[150]—a boulder-clay below the main mass of the sands and gravels has been reported from the Lea valley near Hertford.[151]

The gravels of the Clacton-on-Sea stage,[152] which are closely linked with the Lower Gravels of Swanscombe both faunistically and culturally, have been shown on the basis of heavy minerals to be almost certainly later than the Great Chalky Boulder-clay, and by pollen analysis to belong to a warm-temperate forest period (great interglacial ?) with *Elephas antiquus*, *Dicerorhinus*, *Bos primigenius* and *Dama clactoniana* (= *Cervus browni*) and mixed oak forest (*Alnus*, *Ulmus*, *Quercus*, *Corylus*) passing upwards into a period of declining warmth with a preponderance of *Abies*.

Those who reject this interpretation of the Hornchurch and comparable sections place the Chalky Boulder-clay after the Taplow Terrace[153]: the

terraces pass beneath boulder-clay or fluvioglacial deposits in Essex[154]; and implements like those of Swanscombe (including a Clactonian III implement) occur below boulder-clay near Hertford.[155] They also find no glaciation in the Thames valley before the Flood Plain Terrace and Ponders End stage.[156] This "preglacial" age of the terrace, anticipated by some of the earliest investigators,[157] accords with the contention that Britain, like other regions, had only one cold period, as judged from its molluscan and mammalian fauna (see p. 913). Thus the Cromerian fauna, e.g. *Trogontherium cuvieri* and *Mimomys*, occurs in the highest terrace, as at Swanscombe (see above); the Cromerian (Upper Freshwater Bed) *Macacus pliocoenia* Owen is found at Grays Thurrock[158]—the "Elephant Bed" of Clacton with its warm fauna (*Elephas antiquus*, *Diceros megarhinus*, *D. leptorhinus*) and flora, including Canary laurel and *Euphorbia hibernica* (now found in the British Isles only in Cornwall, Devonshire and south-west Ireland), is an intermediate locality of Taplow Terrace age[159]; and the faunal succession shows no sign of a glaciation before the Ponders End stage which corresponds, it is said, with the Arctic Freshwater Bed.[160]

The gravels containing the Swanscombe skull (= early-middle Acheulian) belong to the temperate interglacial between the Great Eastern glaciation of East Anglia and the cold phase represented by the Main Coombe rock of the Thames valley[161] (Little Eastern Glacier) which preceded the Taplow Terrace aggradation.[162] This is in accord with the mammalian, molluscan and floral evidence.[163] The Slades Green trail is equivalent to the Hunstanton Boulder-clay glaciation and the loess horizons of Ebbsfleet are coeval with the last glaciation.[164]

The middle Thames between Brentford and Goring Gap repeats in broad outline the same history but provides an additional terrace, the Iver Terrace, between the Boyn and Taplow terraces.[165] The terraces about Oxford,[166] which are a vital link by way of Moreton Gap between the lower Thames and the drifts of East Anglia on the one hand and of the south-west and west country and the Midlands on the other, also confirm and amplify the story of the lower Thames. The warm fauna (*Elephas antiquus*, *E. trogontherii*, *Diceros leptorhinus*) of the Hanborough Terrace (with an unrolled early Acheulian or late Abbevillean implement)—this terrace is the equivalent of the Three Pigeons Terrace of the Thames and the Silchester Terrace of the Kennet—is also found in the upper part of the Summertown-Radley Terrace (*Hippopotamus*, *Elephas antiquus*, *Diceros leptorhinus*, *Felis spelaea*, *Corbicula fluminalis* with middle Acheulian or Micoquean) but is followed in the lower part of this Terrace (= Taplow Terrace) by a cold fauna (mammoth, woolly rhinoceros, reindeer). Both horizons in the terrace yield rolled Chellean and lower Acheulian implements and correspond to the Lower Boyn Hill or Furze Platt Terrace and middle Barnfield gravels of Swanscombe. The amplification is in the establishment of three cold periods, a first indicated by the Northern Drift and by the Coombe and Freeland terraces (which represent its outwash) and by striated erratics in the Wolvercote Terrace (the outwash equivalent of the Chalky-Jurassic Boulder-clay farther east[167]—it contains abraded Chellean), a second by the cold fauna of the lower part of the Summertown-Radley Terrace (= Furze Platt Terrace), and a third by the "trail" which festooned the gravels.

The Wolvercote Channel contains sands and gravels which reveal a complete change from warm to cold climate. The lower gravels enclose remains

of *Elephas antiquus*, *Diceros leptorhinus*, *Cervus elephas*, *Bos primigenius*, *Bison priscus* and *Equus caballus*, i.e. a fauna similar to that of the upper horizon of the Summertown-Radley Terrace, with abraded Chellean and unrolled Levalloisian implements. The overlying trail has remains of arctic plants.

W. J. Arkell[168] correlates the Oxford, London basin and Midland successions as follows:

Midland Drifts	*Oxford*	*London*
Little Welsh Ice	Buried Channel	
	Northmoor Terr.	Taplow W
Irish Sea Ice	Pre-Northmoor Terr. erosion	R?
Avon Terr., 3 and 4	{Summertown Terr. Wolverton Channel Wolverton Terr.	Late Boyn Hill Clacton Early Boyn Hill
Great Welsh Ice Main Eastern Ice }	Moreton Drift	Great Chalky Boulder-clay } M
Smitherfield Gravels	Hanborough Terr.	Silchester Terr.
Great Welsh Ice Main Eastern Ice }	{Campden Tunnel Drift Combe and Freeland Terr. Northern Drift	Gravel Terr. Older Drift } G

Periods of low sea-level and erosion probably separated the interglacial epochs of high sea-level and aggradation represented by the terraces, e.g. the Boyn Hill and Taplow terraces. These low levels are shown by the benches, e.g. the Taplow Bench which is below sea-level in the Dartford area (see above), by the descent of the coombe-rock and trail to below sea-level,[169] and by the buried or sunk channels, of which three are known, viz. the Hedge Lane, Ponders End and Tilbury (Hackney Wick) stages,[170] all probably belonging to the last glaciation (Upper Chalky Drift, Hunstanton Boulder-clay and Scottish Readvance?). There was most probably a glaciation in the Thames valley between middle and upper Acheulian[171] (= Acheul V), corresponding to the boulder-clay in Breckland at this horizon.[172]

The tributaries of the Thames,[173] e.g. Stour, Mole, Wey, Blackwater, lower Medway and Swale, corroborate the sequence of the main valley—the Taplow Terrace in the Mole is duplicated at 21 m and 15 m respectively. The Clacton Channel deposits belong to the same interglacial as the 100-ft terrace.[174]

Cam, Severn and other terraces. The deposits of the Cam at Cambridge[175] (fig. 203) which succeeded a Chalky Boulder-clay—foreign erratics (Millstone Grit, Cheviot and Scandinavian igneous rocks) betray this cold period in the gravels—show palaeontologically but one warm period ended by a cold one. The warm fauna of the oldest horizon, the Lower Barnwell Village Beds and Barrington Gravels (with *Corbicula fluminalis*, *Belgrandia marginata*, *Unio littoralis*, *Hippopotamus* and worn Chellean and Acheulian implements) is followed by the beds in Travellers' Rest Pit, which have few fossils and implements of Acheulian and early Levallois type and probably mark the oncoming of the Little Eastern Glacier, and in the Upper Barnwell Village Beds by a cold period (*Elephas primigenius*, *Tichorhinus antiquitatis* and Mousterian implements). As in the Thames, this cold period culminated in still lower beds (Barnwell Station Beds), with the addition of the reindeer fauna and an arctic flora[176] (implements are lacking) indicating in its percentage of arctic-alpine plants an even severer climate than in the Lea valley—it has been suggested that the cold plants at Barnwell and in the Lea valley were washed down from higher levels.[177] Recently, an interglacial deposit, of Barnwell Terrace age, has been discovered at Histon Road,

Cambridge,[178] which is to be correlated with an immediately post-Eemian stage. It had a *Carpinus* dominance like that which on the Continent occurred immediately after the climatic optimum of the last interglacial.[179]

Recent evidence suggests that the Travellers' Rest Pit gravels may be the oldest in the district and that the Barnwell Village gravels and possibly the Barrington *Hippopotamus* beds are younger and belong to the last interglacial epoch (King, 1955).

Accumulations in the Great Ouse basin[180] also reveal by the contained erratics an early glaciation and by their fauna a climatic worsening from the warm species (*Corbicula fluminalis*, *Hippopotamus*) which lived in the transgressing March–Nar sea (see p. 1007) to the cold climate of the lowest levels.

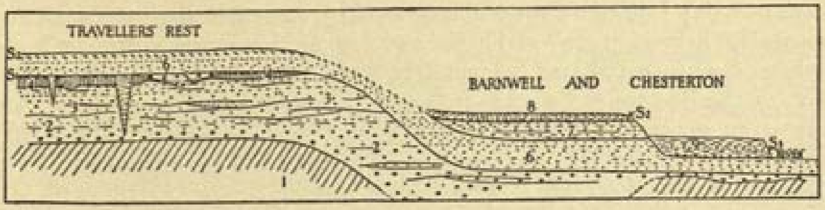

FIG. 203.—Diagrammatic composite section of the terraces of the Cam at Cambridge. *Rp. B.A.* 1938, App. p. 16, fig. 5.

9. Lower Terrace: fine gravel and silt with poorly marked solifluxion band (S_3).
8. Loams and gravels with cold fauna and solifluxion band (S_2).
7. Middle Terrace: gravels with warm fauna and late Clacton-Levallois-Acheul industry.
6. Interglacial aggradation gravels. S_1. Solifluxion band with frost cracks and polygonal soil forms of Upper Chalky Boulder-clay age.
5. Upper Chalky Boulder-clay in lenses.
4. Loess-loam.
3. Uneven-bedded series of Travellers' Rest Pit, with rolled lower palaeolithic tools and cold fauna.
2. Lower even-bedded series of Travellers' Rest Pit, with erratics derived from Lower Chalky Boulder-clay.
1. Gault with surface rucked by sludging.

At Biddenham near Bedford, the 40-ft (*c.* 12 m) gravels with the famous middle Acheulian implements rest in a valley cut into the Chalky Boulder-clay, thus reproducing the Hornchurch and other sections of the Thames (see above) and agreeing with the evidence at Breckland,[181] in the Midlands,[182] and in the Oxford district[183] where the valleys were similarly cut before the deposition of the middle Acheulian gravels.

The Warwickshire Avon[184] likewise shows a cold climate represented by fluvioglacial spreads on the highest ground and a series of well-developed terraces, the highest terrace (No. 4) enclosing a warm fauna (*Corbicula fluminalis*, *Unio littoralis*, *Belgrandia marginata*, *Hippopotamus*, *Elephas antiquus*) and late Acheulian or Levalloisian implements, followed by a No. 3 terrace with *Hippopotamus*, *E. antiquus* (possibly), *Unio littoralis* and *Belgrandia marginata* and a lower terrace (No. 2) with a cold fauna (mammoth, woolly rhinoceros, reindeer). This is the equivalent of the Main Terrace of the Severn which contains Scottish and Cumbrian erratics and remains of mammoth and woolly rhinoceros and includes the outwash of the Newer Drift. Above this terrace in the Severn is a higher, Kidderminster Terrace (= terraces 3 and 4 of the Avon), with *Elephas antiquus* and Acheulian implements—it grades with a 65 ft (*c.* 20 m) sea—and below it a lower, Worcester

Terrace with the cold mammalian fauna[185] which is the first terrace to be traced on the upstream side of the Ironbridge Gorge.

The Severn and Avon were throughout the Ice Age the principal lines of drainage from the ice-front and during the later stages (see p. 1199) also received waters from the upper Severn that should have gone to the Dee and Mersey. For these reasons, the valleys are considerably overdeepened[186] and the sequence of changes, based upon physiographical evidence, is generally unsupported by fossils or implements. The Woolridge Terrace, the highest in the Severn, contains Bunter pebbles with some flint, Croft syenite and possibly North Welsh erratics which suggest that the gravels are either fluvioglacial or derived from earlier glacial deposits.

The terraces of the Trent,[187] which contain flints and therefore are newer than the Chalky Boulder-clay, are in general agreement with those of the Avon. Thus the high-level gravels of Upper and Lower Hilton (90 ft and 40 ft above alluvium) may be correlated respectively with No. 4 and No. 3 terraces of the Avon and the Beeston terrace (30 ft above alluvium) with No. 2—they contain implements ranging up to Levalloisian and late Acheulian; the Allerton terrace of the Derwent[188] suggests both by its level and its hippopotamus that it belongs to No. 3 terrace. The lowest terrace of the Trent, with its *E. primigenius* and *Tichorhinus antiquitatis*, seems to be the equivalent of No. 2 terrace of the Avon and probably of the lower terrace of the Tame.

In the area between Coventry, Rugby and Leamington in the Midlands of England the following succession has been established[189]:

Newer Drift

5. River-terraces of the Avon which fall to the south-west and cross the plane of the base of the older drifts.

Older Drift

4. Dunsmore Gravel and Chalky Boulder-clay.
3. Walston Series, which consists of stoneless clay or clay with only occasional pebbles and was deposited in "Lake Harrison" (see p. 1190).
2. Bagington-Lillington Gravels, deposits of interglacial streams, which contain *Elephas antiquus*, *E. primigenius*, *Bos primigenius*, *Equus caballus*, *Rangifer tarandus*, *Tichorhinus antiquitatis*, *Sus scrofa* and *Hyaena crocuta*. The Bagington type has Bunter material only, while the Lillington type has Jurassic material also.
1. Bubbenhall Clay, a very early drift which fills a preglacial valley falling to the north-east.

South coast valleys. Rivers and marine beaches in southern England repeat the story of the Thames and the rivers just mentioned; the equivalents of the Boyn Hill and upper and lower Taplow terraces have been determined in the Axe, Otter, Dart and Bovey-Teign.[190] The highest Pleistocene terrace in the Hampshire Avon,[191] which has yielded Strépyian, Chellean and Acheulian implements, was preceded by a cold period and was followed by a second cold period when the Fishterton brickearth with mammoth and other arctic mammals was laid down. In the Stour near Bournemouth,[192] the 130-ft (40 m) terrace (= Boyn Hill Terrace) contains middle Acheulian (especially Acheul III)—other terraces occur at 300 ft (*c.* 92 m; Sicilian ?), 250 ft (*c.* 76 m; Upper Ambersham Terrace), 190 ft (*c.* 58 m; Ambersham

Terrace), 165 ft (*c.* 50 m; Sleight Terrace), 90 ft (*c.* 28 m; Upper Taplow Terrace), 50 ft (*c.* 15 m; Taplow Terrace), 41 ft (*c.* 12·5 m; Muscliff Terrace) and 23 ft (*c.* 7 m; Christchurch Terrace).

In the Portsmouth area,[193] terraces at 100, 50 and 15 ft (30, 15 and 4·5 m) grade into marine beaches. The 100-ft terrace has a warm fauna with Acheulian implements, e.g. at Portsdown and Goodwood, the 50-ft terrace has a cold fauna with Mousterian and rolled Acheulian implements (this cold horizon[194] is traceable to Brighton, Aldrington, Portslade-by-the-Sea, and into Hampshire and the Isle of Wight), while drift erratics from Selsey to Lee-on-Solent (see p. 1097) and gravels with mammoth and reindeer down to −50 ft (15 m) O.D. distinguish the lowest level.

(*d*) *Marine Interglacial Accumulations*

Marine accumulations, mostly gravels, occur in England both within and without the glaciated area. Those without are found at West Wittering[195] (Sussex), Ilford[196] (Essex) and (with *Corbicula fluminalis*) at Middlezay[197] (Somerset); those within at Clacton[198]—the associated flora at Clacton and West Wittering signifies a dry, warm climate[199]—Woodston[200] (Peterborough), March[201] and the Nar valley,[202] Mersea Island[203] (Essex), Kirmington[204] (Lincolnshire), Kelsey Hill[205] (Holderness) and in south Wales and south Ireland (see p. 1252).

South coast. Along the Sussex coast, as at Selsey, Goodwood and West Wittering, marine muds with molluscs of a southern type associated with *Corbicula fluminalis*, *Hydrobia margarita* and the southern European maple, were preceded presumably (direct superposition cannot be proved) by a sea with drift erratics (see p. 1097) and followed by the recurrence of arctic conditions of the Brighton coombe-rock and mammoth. While archaeological evidence distinguishes between a 90-ft (28 m) and a 135-ft (41 m) beach,[206] the two appear to mark the period of rising sea-level that caused prolonged aggradation in the southern rivers during Clactonian-middle Acheulian, i.e. 100-ft (*c.* 30 m) terrace time. The 100-ft beach (Tyrrhenian) contains middle Acheulian, the 50-beach (Main Monastirian) no implements as yet, and the 15–25 ft (4·5–7·5 m) beach (late Monastirian) "Mousterian" or Levalloisian.[207] Three horizons of coombe-rock overlie the 100-ft (30 m) beach, two horizons the 50-ft (15 m) beach (which occurs at Portland and Selsey), and only one horizon the 15-ft (4·5 m) beach: their solifluxion conditions marked the times of glaciation and falling sea-levels.

March gravels. The March gravels, which contain Jurassic fossils and erratics apparently derived from the Chalky-Jurassic Boulder-clay, are current-bedded, flint gravels of variable thickness and character that cap isolated hills of Kimmeridge Clay and till in the Fens. Their commonest shells are *Macoma balthica*, *Cardium edule*, *Turritella terebra*, *T. communis*, *Buccinum undatum*, *Mytilus edulis* and *Littorina litorea* (with derived *Corbicula fluminalis*), a marine fauna which lived in 5–15 fathoms in a colder North Sea like that off Denmark or south Norway to-day[208] though a few shells indicate a warmer sea. The gravels are survivals of a much-denuded sheet[209] which, of the age of the Hessle gravel[210] and the warm bed in the Cam at Cambridge (see p. 1004), was laid down interglacially as sand banks in a March–Nar sea[211] (see below), probably the last interglacial, though their shells include no "Lusitanian" forms and are referable rather to the Skaerumhede series than

to the Eemian.[212] They succeeded the Great Chalky Boulder-clay, preceded the Chalky Drift and are probably late Levalloisian in age.[213] The solifluxion deposits overlying them have been referred to the Hunstanton or a later period.[214]

Nar valley brickearths. The Nar valley brickearths, traceable from Narford to Watlington in the Nar valley, contain *Turritella communis*, *Littorina litorea* and *Ostrea edulis* (*Corbicula fluminalis* at Kings Lynn) together with the *fauna chaude* and remains of mammoth, woolly rhinoceros and *Cervus elephas* and with Chellean, Acheulian and Mousterian implements. These bluish, sandy clays, to judge from the height of the localities and the nature of the shells, are the deltas which the Great Ouse, Cam and other rivers built into the sea that submerged the present Fens and Wash to a depth of 30–50 ft (9–15 m).[215] They mark a period of aggradation[216] when the marine gravels, 20 ft (*c*. 6 m) thick under the till at Eye[217] near Peterborough, were accumulating; this is shown by the nature of the gravels, by their perfectly preserved shells, by the drift wood and by the big, flat slabs of Oxford Limestone bored by *Pholas*.

Kirmington. The Kirmington beds repose in a sheltered valley in the eastern foot of the Lincolnshire Wolds at *c*. 100 ft (30 m). Sandwiched between the Purple and Hessle boulder-clays[218] or between the lower and upper Purple boulder-clays,[219] they constitute an undisturbed series of estuarine and freshwater beds overlain by a thick gravel of large, well-worn flints. Their laminated loams and sands or muddy silts and marsh plants denote a subarctic climate. With their indigenous and perfectly preserved shells (*Scrobicularia piperata*, *Hydrobia ulvae*, *Cardium edule*, *Mactra subtruncata*, *Mytilus edulis*), thin estuarine forms of *Tellina baltica*, foraminifera and horns of *Cervus*—*Corbicula fluminalis*, known elsewhere in north Lincolnshire, has not been observed here—and remains of plants including spruce, they form an important interglacial horizon. Though tentatively assigned to the lateglacial[220] or a subordinate episode of a single glaciation[221]—they have been regarded as a transported raft—or to a narrow glacier-lake,[222] the horizon is usually interpreted as truly interglacial.[223] It contains upper palaeolithic implements.[224]

Kelsey Hill gravels. The Kelsey Hill gravels consist of coarse gravel, fine shingle and current-bedded sand, the whole totalling 80 ft (*c*. 24 m) in thickness. They contain numerous erratics (perforated by *Pholas* and *Saxicava*) and worn and broken shells of *Corbicula fluminalis* (extremely plentiful and occurring significantly where the Humber breaches the Wolds) and many marine species,[225] including the warm shells *Cytheria chione* and *Venus gallina*. They also enclose early Mousterian implements[226] and remains of mammoth, woolly rhinoceros, reindeer and *Bison priscus*, some marked by teeth of hyaena.

These marine gravels, which like those of Burstwick rest in hollows in the Purple Clay,[227] were probably incorporated by the ice in its last advance,[228] possibly as outwash. They are older than the Hessle Clay and doubtless equivalent to similar gravels traceable round most of Holderness,[229] though they have recently been regarded as subglacial in origin.[230]

All the marine beds mentioned in this section were probably contemporaneous[231]; they point to a submergence of eastern and southern England to a height of 50–100 ft (15–30 m); Kelsey may have been an interglacial

Spurn Point.[232] Why there were no signs of submergence in the Vale of York and Vale of Trent long remained a mystery—the plains, it was suggested,[233] were then occupied by ice. The problem has now been solved by the discovery[234] of strandlines in the form of gravel patches at *c.* 100 ft (30 m) on the flanks of the Vale of York skirting the Pennine Chain and the Wolds, e.g. between Tadcaster and Doncaster and at several places between Market Weighton and the Humber, south of the Escrick moraine (see p. 1193). The lower ends of the dry valleys are at about this level, and at Doncaster the Don has deposited a delta of this date. The Leeds (Kirkstall) hippopotamus (see p. 792) and the hippopotamus in the Trent gravels (see below) may belong here. A similar beach occurs east of the Yorkshire Wolds.[235] A later level occurs at 25 ft (*c.* 7·5 m) O.D. R. G. Carruthers,[236] however, regards the so-called beach around the Vale of York as hillwash poured on to the margin of a residual ice-mass, the York and Escrick moraines as bucklings of recently released subglacial detritus, and the lacustrine clays outside the Escrick moraines as subglacial and washed remnants of former lenses or beds of till.

(*e*) *Extent of Deglaciation*

A widespread retreat in the British Isles, amounting possibly to complete deglaciation, is implied by the "warm" river-terraces and marine deposits of the south and east of England, described above. Certain other evidence which we may now briefly examine also suggests it.

A temperate flora has been gathered from Pleistocene deposits[237] at Stoke Newington, Wolvercote, Hitchin and Stacklewell. At Brandon, Norfolk,[238] gravels which rest on Upper Chalky Drift and are overlain by a glacial deposit, possibly of the age of the Hunstanton Boulder-clay, contain early Acheulian implements with molluscs and mammals indicating open grassland and a warm climate. Temperate seed-bearing peats near St. Bees[239] have been disturbed and contorted by an ice-thrust from the sea (Scottish Readvance). The beds of peat and vegetable matter, up to 25 ft (*c.* 7·5 m) thick and hundreds of yards long, in Furness,[240] though claimed to be interglacial,[241] are apparently postglacial.[242]

Other deposits which may be interglacial include the black, carbonaceous matter in moraines 3 miles (*c.* 5 km) south of Carnforth[243]; leaf-clays with plant debris and roots below boulder-clay at Crewe[244]; beds with plants and hippopotamus in Trent gravels near Derby[245]; and loess, up to 12 ft (*c.* 3·8 m) thick, containing molluscs and resting in fissures and hollows in the Magnesian Limestone and in depressions in pure Scandinavian drift at Castle Eden Co. Durham.[246] The deep decay of many of the boulders in this drift also demands a prolonged period of exposure to atmospheric weathering.[247]

The mammalian evidence is particularly significant[248] (figs. 204, 205). One or more members of the southern trio (*Hippopotamus*, *Elephas antiquus*, *Rhinoceros leptorhinus*) have been found in Lincolnshire (Burgh), Holderness (Aldborough, Bridlington, Kelsey), Vale of York (Bielbecks, Leeds), Yorkshire Dales (Raygill, Victoria Cave Settle), Staffordshire (Manifold valley), Lancashire and Cheshire (Adlington, Blackpool, Coppenhall) and in the Vale of Clwyd (Cefn cave). The cave forms (cave lion, cave hyaena, cave bear) have a similar distribution; for one or more of them have been found in Holderness (Barmston, Bridlington, Hornsea), Vale of York (Bielbecks),

Yorkshire Dales (Moughton, Raygill, Victoria Cave) and Vale of Clwyd (Cae Gwyn, Cefn and Fynnon Beuno caves). Mammoth and woolly rhinoceros, either alone or together, have a wider and even more significant distribution in drifts and caves as far north as Scotland and as far west as Ireland. The localities include Durham (West Hartlepool), Holderness (Brandesburton,

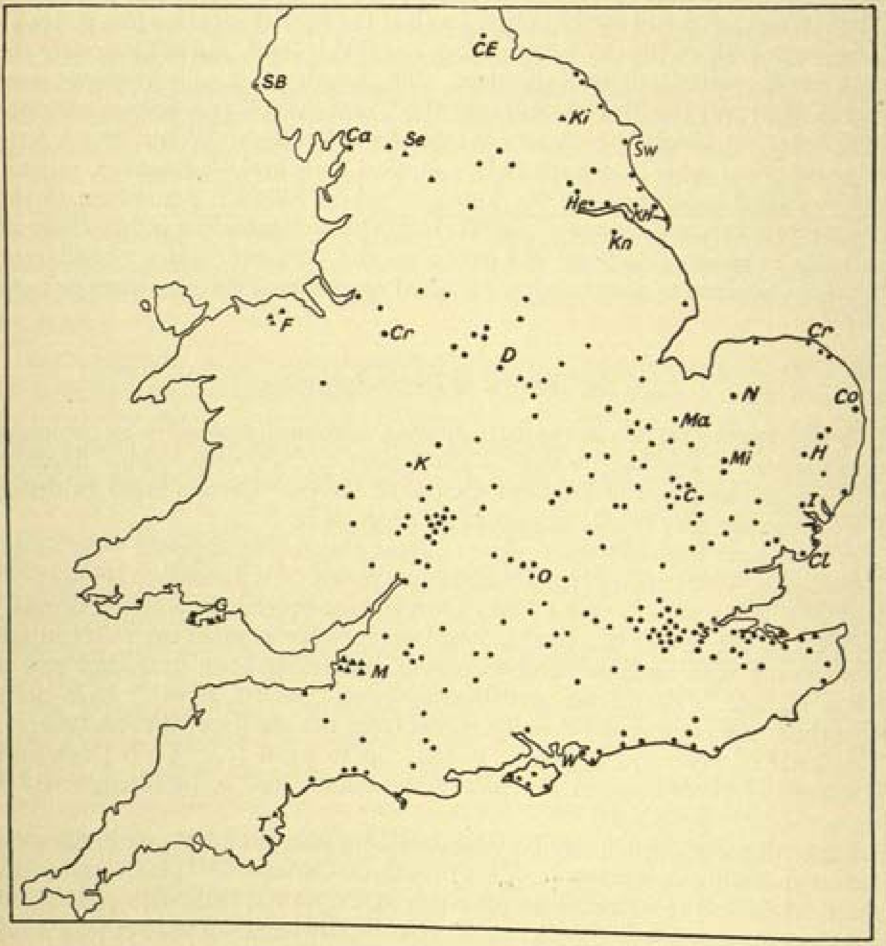

Fig. 204.—Map of England and Wales showing interglacial localities. C, Cambridge; Ca, Carnforth; Cl, Clacton; CE, Castle Eden; Co, Corton; Cr, Cromer; Cr, Crewe; D, Derby; F, Flintshire; G, Gower; H, Hoxne, He, Hessle; I, Ipswich; K, Kidderminster; Ki, Kirkdale; KH, Kelsey Hill; Kn, Kirmington; M, Mendips; Ma, March; Mi, Mildenhall; O, Oxford; S, Swanscombe; SB, St. Bees; Se, Settle; Sw, Sewerby; T, Torquay; W, West Wittering. Caves (triangles).

Bridlington, Elloughton, Harswell, Kelsey, Kilnsea), Vale of York (Bielbecks, Cayton Gill, Fulford, Overton), Yorkshire Dales (Norwood, Raygill, Ripley), Lancashire and Cheshire (Adlington, Marbury, Northwich, Runcorn, Sandbach, Bolesworth, Warrington, Wallasey), Vale of Clywd (caves mentioned above), Midland Valley of Scotland (see p. 809) and Ireland (see p. 809).

The remains of the cold duo in Scotland and Ireland, like those in Scandinavia (see p. 963), doubtless belong to an interglacial age,[249] though one still

moderately cold, as the *Pecten islandicus*, *Tellina calcarea* and *Leda oblonga* associated with them at Kilmaurs[250] seem to imply. Yet true interglacial deposits, the beds of Benholm,[251] Kincardineshire (= sands, gravels and peats at 60 m and 1½ miles (2·5 km) from the sea between grey basal boulder-clay below and red Strathmore till above), are rare in Scotland; they include (fig. 205) the interglacial fossiliferous beds[252] (possibly lateglacial or later[253])

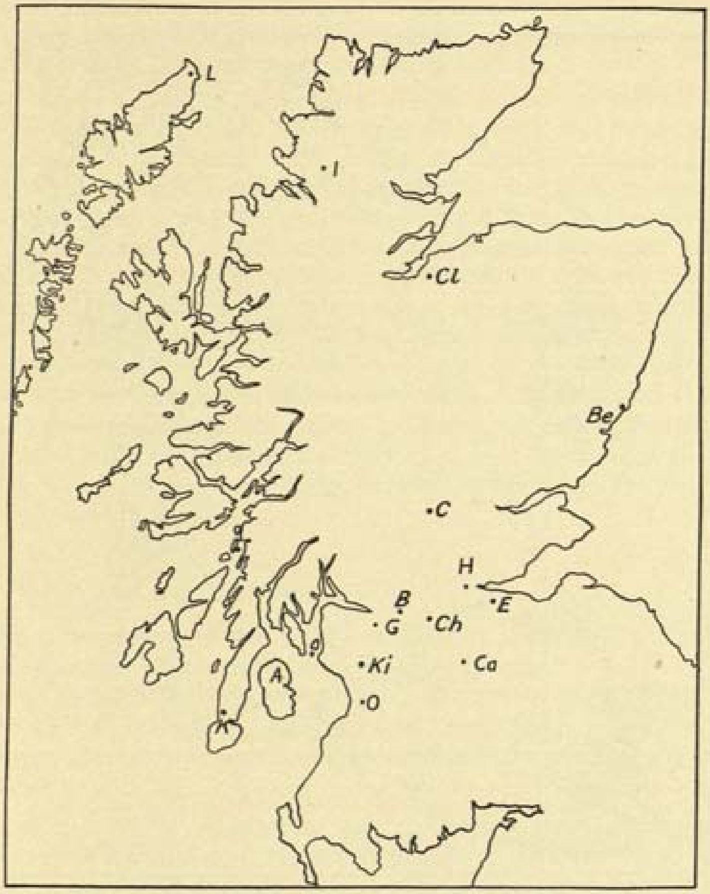

FIG. 205.—Map of the interglacial and interstadial localities in Scotland. Mammoth, Dreghorn (D), Kilmaurs (Ki), Chapelhall (Ch), Headswood (H); woolly rhinoceros, Bishopbriggs (Bi), reindeer, Glasgow (G), Carluke (Ca), Inchnadamph (I); plants, Kilmaurs (Ki), Chapelhall (Ch), Hailes & Redhill quarries, Edinburgh (E), Benholm (Be); palaeoliths, Comrie (C); marine beds, Kintyre (K), Arran (A), Clava (Cl), Butt of Lewis (L).

of Red Hall quarry and Hailes Quarry near Edinburgh, of Chapelhall near Airdrie, and of Cowden Burn, Renfrewshire, and the reindeer remains of Glasgow.[254] The fauna in the cave at Inchnadamph, Sutherland,[255] which embraces arctic fox, bear and over 400 young reindeer and is associated with horn implements, charcoal and human skeletal remains said to be Magdalenian or earlier, is very lateglacial: the cave was uninhabitable until almost the whole of the Scottish Highlands had been liberated[256] (Alleröd period).

Interglacial conditions in Scotland may also be indicated by the complexity of the ice-movements revealed for the east of the country (see p. 756) and by the derived peat, found in places in moraines of the Strathmore ice in the Aberdeen district.[257] Despite claims to the contrary,[258] no human implements had been found in a Scottish Pleistocene deposit until recently when a sand and gravel layer, overlain by till near Comrie, Perthshire, yielded an oval flake of Levallois type.[259]

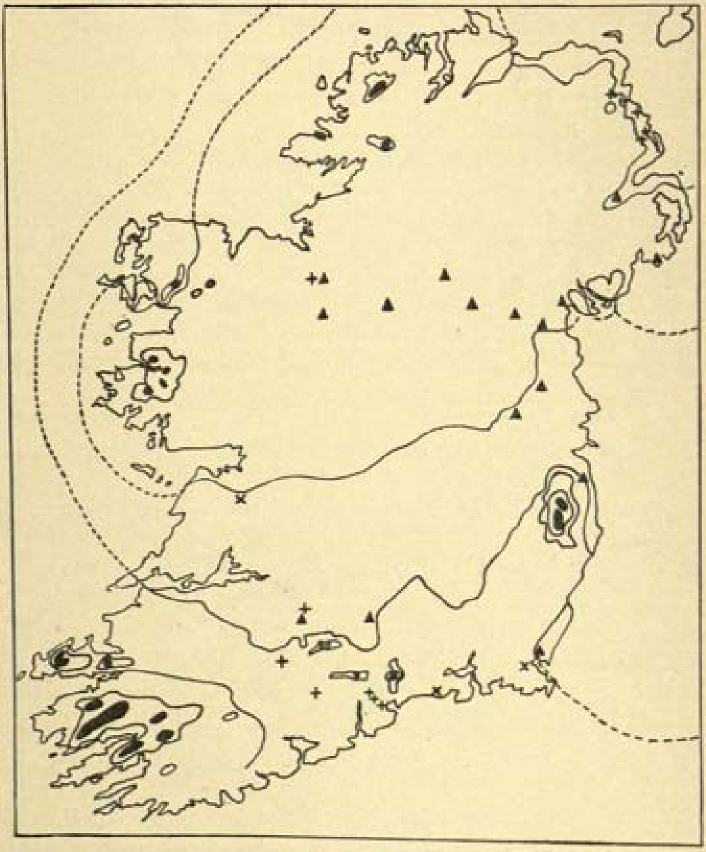

FIG. 205a.—Map of Ireland showing interglacial (×) and lateglacial (▲) localities, sites of Pleistocene mammals (+) and limit of newer drift and lateglacial stages (last stage in black).

Irish interglacial deposits occur in Co. Antrim, at Gort, Co. Galway,[260] where they consist of a soil with Scotch fir and spruce and hazel nuts buried under 20 ft (6 m) of till, and of probably Mindel-Riss age, at Ardcavan, Co. Wexford, and Kilbeg, Co. Waterford.[261] Peats in the drift of Co. Tipperary, Co. Galway and of Leix may also be interglacial[262]—a weathered deposit below the Riss drift at Nemestown, Co. Wexford, may represent the Mindel glaciation and have supplied erratics to the infraglacial beach. Genuine palaeoliths have yet to be found in Ireland. Those so claimed are either natural, viz. from Killiney Bay, Co. Dublin, and the raised beach and other deposits in Co. Antrim,[263] or of uncertain age at Rosse's Point, Co. Sligo.[264]

The human skeleton from Kilgreany, Co. Waterford, though claimed to be upper Palaeolithic,[265] is apparently Neolithic.[266]

An interglacial recession is implied by the palaeoliths (or pieces alleged to be such) within the area of the Newer Drift, e.g. from Settle (Victoria Cave), Eskdale, Nidderdale, Bridlington and other Yorkshire localities[267]—middle Acheulian, of presumably Mindel-Riss age, has been found near Doncaster[268]; from gravels above the Scandinavian drift of the Durham coast[269]; and from the drift of Lancashire and Cheshire,[270] North Wales,[271] Lincolnshire[272] (Kirmington) and the Isle of Man[273] where an interglacial marine horizon lies beneath the drift plain of the northern part of the island.

The interbedded marine clays of Scotland, all peripheral to the Highlands, are probably also interglacial. They include those at the north end of the Isle of Lewis,[274] with such warm shells as *Ocenebra erinacea* and *Sipho jeffreysianus*; those up to 100 ft (30 m) or more about Kilmaurs, Ayrshire (see above); those beneath moraines in Arran[275]; and those *in situ* at 135–199 ft (41–61 m) in Kintyre[276] which represent a submergence of 100 m. In the most celebrated of all the occurrences, the marine clays with shells, many entire and with epidermis intact, lie beneath 45 ft (14 m) of till 500 ft (*c.* 150 m) A.S.L. at Clava in Strathnairn.[277] They were possibly conveyed from preglacial marine clays about Inverness,[278] though such transportation is irreconcilable with the extraneous nature of the bulk of the enclosed pebbles and with the known ice-movements. More probably, they are *in situ* and denote an interglacial submergence[279] of at least 500 ft (*c.* 150 m) in this part of Scotland—the waters may have restricted the mammoth to the country south of the Forth and Clyde.[280]

3. Succession and Correlations

The disentanglement of the British succession is extremely difficult. In the reconstructions which have been attempted, one,[281] two,[282] three[283] or four[284] glaciations have been recognised. A correlation of the horizons in the several British areas where they are best developed is set out in the subjoined table. It is by no means unimpeachable or without its difficulties or inconsistences.

Oldest drifts. The oldest drifts, all probably roughly contemporaneous, are the Norwich Brickearth of east Norfolk (see p. 766), the Drab Series of the Basement Clay of Holderness (see p. 763), the Scandinavian Drift of Co. Durham (see p. 749), the derived erratics in the southern terraces[285] (see pp. 1002, 1004), and the Plateau Drift, with its Scandinavian erratics, of the upper Thames (see p. 629). The peculiar lithology and the characteristic boulders of the Scandinavian Drift differentiate it from the later boulder-clays. It is frequently decalcified and weathered and eroded into outliers—the valley system of East Anglia was cut through it (see p. 992); W. S. Bisat[286] in a dissentient view places the Basement Clay in the Newer Drift or the opening phase of the third glaciation. To this early age also probably belong the lower till of Northamptonshire, the Bubbenhall clay of the Coventry, Rugby and Leamington area, all of which are in a fragmentary condition because of the weathering which took place during the great interglacial epoch which followed.[287]

At this time, ice existed in the North Sea, in Wales (First or Great Welsh

Drift) and in the Midlands (Pennine Ice) and the Welsh and Pennine ice were confluent in the Midlands (see p. 774).

Newer Drift and its equivalents. The Newer Drift, which has been generally thought to include the Hunstanton Boulder-clay and the Hessle Clay (cf. p. 1214) and the till and associated deposits of the country within the "York Line", has been correlated with the Mousterian[288] but is probably early Magdalenian.[289] Thus, while the late-palaeolithic stations of Britain[290] occur outside this line ("Bristol Channel-Wash Line" of the early archaeologists[291]), e.g. in Kent (Halling), South Devon (Kent's Cavern), Somerset (Cheddar, Aveline's Hole), Pembrokeshire (Monkton, Hoyles Mouth), Lincolnshire (Sheffield's Hill, Willoughby, Risby Warren), Norfolk (Wangford Warren), Derbyshire (Creswell caves) and in the Midlands (Ancaster, near Birmingham, and Coventry, and south of Warwick), there are neither Pleistocene mammals nor palaeoliths on the surface of the Newer Drift[292]: they were early thought to be excluded[293] by a glacial sea, the glacial cold or by ice. Any upper palaeoliths within the "York Line" are either found in caves or buried or enclosed by the latest drift (see above). Thus early Mousterian implements[294] have been discovered beneath the Hessle Clay in east Yorkshire and in gravels at Hessle and Burstwick between that clay and the lower Purple Boulder-clay; the latest cultural stage before the Hessle Clay was early Aurignacian; Aurignacian and Solutrean implements occur in the Flintshire caves,[295] e.g. Fynnon Beuno and Cae Gwyn; Aurignacian and Proto-solutrean remains are found in Paviland[296] (south Wales), with abundant horses indicative of Aurignacian age—Magdalenian is absent from the above caves; Aurignacian and late-Levallois implements occur in the raised beach at Morston[297] (see p. 772); and upper palaeoliths[298] are embedded in the uppermost till of Holderness, at Kirmington and in the Hunstanton Boulder-clay.

The extraglacial equivalents of the Newer Drift are the Ponders End stage of the Thames (see p. 1001) which is overlain by an early mesolithic site (Broxbourne) sealed under Boreal peat[299]; the lowest deposits in the Cam, Great Ouse, Severn and Avon basins (see pp. 1004, 1005); the brickearths[300] of Kent (Swalecliff, Studhill Cliff, Upchurch, Dover, Folkestone, Halling, Cuxton), Berkshire (Chilton), Essex (Chelmsford) and the Isle of Wight (Freshwater); the solifluxion deposits of the Midlands[301]; the "head", upper Coombe-rock and arctic beds along the south coast (see p. 1081); the upper Coombe-rock and upper cave-breccias of the Bristol area[302]; the "head" of the west Midlands and west Yorkshire (see p. 1081); the trail,[303] the latest deposit to contain palaeoliths, which passes into the low-level deposits of the Thames,[304] overlies upper Mousterian and Aurignacian implements, e.g. near Ipswich,[305] and encloses Solutrean artefacts in places[306]; the highly contorted brickearths and gravels of Suffolk[307] and the solifluxion slopes[308] of the south Pennines and about the Vale of York, and the ice-wedges in north-east Yorkshire.

The small local glaciers[309] on Charnwood Forest and the Wrekin may be of this age, as may the torrential gravels, derived from melting snows, on the Clent Hills and Longmynd[310] and the Cotswold Hills (see p. 1080).

This glaciation may have been tripartite: this is suggested by the three sunk channels of the Thames (see p. 1004) and by the three cold phases (= layers of rock-debris and cave-earth with reindeer fauna) in the Pin Hole Cave, Creswell, Derbyshire.[311]

Great Chalky Boulder-clay. One of the most critical horizons in the British succession is the Great Chalky Boulder-clay. It is prevalently held that this preceded the Chellean (Abbevillean[312]), partly because of its relationship to the Thames terraces at Hornchurch and Upminster (see p. 1002). Yet this may be incorrect since like the Cromer Till[313] (at Sidestrand) it encloses Chellean implements, e.g. at Biddenham[314] (Bedfordshire), and the gravels beneath it, e.g. near Rickmansworth,[315] contain Chellean, early Acheulian and early Clactonian implements. The interglacial which separated it from the Upper Chalky Drift, e.g. at Derby Road, Ipswich, at Hoxne and at High Lodge, is the main horizon for certain types of Acheulian and Clactonian. The Upper Chalky Drift followed an interglacial epoch during which the Great Chalky Boulder-clay and overlying outwash were eroded and shallow valleys became occupied by sands and gravels (Bacton Valley Gravel). The drift encloses early Levallois implements ("early Mousterian") and followed the late Acheulian. The Cannon Shot Gravels which interdigitate with it contain unrolled artefacts[316] of Clactonian and Acheulian. Late Acheulian occurs above the Great Chalky Boulder-clay at Ipswich and Mildenhall,[317] or with advanced Clactonian or early Levalloisian has been extracted from the Upper Chalky Drift[318] or preceded this drift at High Lodge and Elvedon.[319] This drift, e.g. near Ipswich,[320] is always definitely earlier than the upper Mousterian, Aurignacian and Solutrean.

While some of these identifications of palaeoliths are probably untrustworthy and probably all need a critical revision, they seem consistent with the view that the Great Chalky Boulder-clay is middle Acheulian in age and corresponds to the Wolvercote Terrace of the Upper Thames and the Main Coombe Rock of the lower Thames (see pp. 1003, 1081). It is of the same age as the Purple Boulder-clay of Holderness and east Lincolnshire—the difference in colour and content is related to the overriding of the Chalk Wolds.[321] Those who recognise a Lower and Upper Purple Clay (see p. 764) equate these with the Great Chalky Boulder-clay and Upper Chalky Drift.[322] Presumably the Great Chalky Boulder-clay is also equivalent to the "older drift" of South Wales and southern Ireland, though this has been equated to the last glaciation.[323]

It has been thought[324] that R. M. Deeley's Pennine Ice of the Midlands was the upstream part of the Chalky Boulder-clay ice of East Anglia and that the Chalky Boulder-clay of the Midlands was coeval with the Chalky Drift of East Anglia.

Interglacial horizons. The Cromer Forest Bed, occasionally stated to be preglacial[325] and transitional between the Pliocene and Pleistocene,[326] is generally deemed to be interglacial[327] and to lie between the glacial epoch represented by the Red Crag, Weybourne Crag and Arctic Freshwater Bed on the one hand (see p. 599) and the North Sea Drift on the other. The equivalent of the 45 m terrace of the Somme (see p. 1258), it is usually made coeval with the first of three interglacial epochs,[328] the Chellean interglacial[329] (to which may also belong the warm trio on the Sewerby beach beneath the Basement Clay of Holderness), though the upper part has occasionally been thought to be middle Pleistocene[330] (Mindel-Riss or Mindel 1–2), a date which seems to follow the adoption of Haug's definition of the base of the Quaternary (see p. 600) and the presence of cold forms in the Forest Bed. The Norwich Brickearth was eroded from north Norfolk. The generally accepted reference to the early Pleistocene, though apparently sustained by

field-relationships, and by the Villafranchian fauna of East Runton and Sidestrand, leaves unexplained the early appearance of certain members of the cold fauna (cf. p. 995). It is doubtful whether, as has been suggested,[331] these were merely migrants from a cold region. The fauna is clearly a mixed one—it contains four species of elephant, such as no other European locality records.

The Cromerian implements,[332] found on the shore at Sheringham, West and East Runton, Cromer, West Mundesley and Overstrand, are ochreous or orange-brown artefacts, often striated as at East Runton. The tools are usually made from heavy flakes but include rostrocarinates and crude Abbevillean forms; seven periods of artificial flaking[333] have been differentiated. The provenance of the implements is uncertain: they have been referred to the Cannon-shot Gravels,[334] to the drifts above the coast,[335] to the Bacton Valley Gravel, or to the base gravels or hard, cemented ferruginous sands of the Cromer Forest Bed itself.[336] They are remanié in the overlying till, e.g. at Sidestrand,[337] and in the Middle Glacials (see p. 771). The Cromer Till has also yielded a typical Abbevillean hand-axe, presumably derived.

The "Middle Glacials" (Corton Sands) of East Anglia, probably Abbevillean in age, may be correlated with the upper terraces (140–100 ft) of the upper Thames and the Dartford Heath gravels in the lower Thames. They have yielded rolled and striated Abbevillean and other lower palaeoliths,[338] mostly Clactonian flakes—the Ipswich skull, thought to have been of this age,[339] is now regarded as of no antiquity.[340]

BRITISH GLACIAL

	Northumberland and Durham	*Holderness and Lincolnshire*	*Yorkshire Dales*	*Trent Valley*	*East Anglia*	*Cambridge*
IV. Glacial (Co, Cy) (W.) (Magdalenian and Mousterian)	Northern B.C. (Cheviot and Scottish)	2. York Line 1. Hessle B.C.	Newer drift	Beeston T.	Hunstanton B.C. Cromer Ridge Chalky Drift	Barnwell Sta. Beds
Riss-Würm (Micoque, late-Acheul)		*Kirmington Sands and gravels*		*Hilton T.*	*March-Nar Sea* *Hoxne and lake-sites* (?)	*Histon* *Barnwell Village Beds*
III. Glacial (Ca) (R.)	Western B.C. (Lake District, Pennines and S. Uplands)	Purple B.C.	Main Glaciation	Outwash of Chalky B.C.	Great Chalky B.C.	Great Chalky B.C.
Mindel-Riss (early Acheul)		*Sands and gravels; Sewerby beach*				
II. Glacial (Be) (M.)	Northern B.C. (Scottish)	Basement Clay	Older till		*Corton sands* Norwich Brick-earth Cromer till	Earlier erratics
Günz-Mindel (Abbevillean) I. Glacial (G.)					*Cromer Forest Bed* Weybourne Crag Red Crag	

The middle terraces in the Thames, Severn, Avon and other rivers which record the ousting of the *faune chaude* by a cold fauna are manifestly interglacial and contemporaneous.[341] Their human cultures link them with the lake-sites or Hoxne interglacial. Some interpose a glaciation between the 100-ft. (30 m) and 50-ft (15 m) terrace in the Thames,[342] or relegate this interglacial to the "Middle Glacials" (as Rutot[343] anticipated), and to a position below the Great Chalky Boulder-clay,[344] the boulder-clay at Upminster, etc., in this view being an outlier of the North Sea Drift.[345] The Clacton flora,[346] which is not that of the Cromer Forest Bed, may belong to this horizon: it reveals the middle and later parts of a climatic cycle in which the mixed-oak forest is succeeded by a coniferous forest of *Abies* and *Picea*, trees not natural in postglacial Britain (see p. 1002). The Clacton interglacial is also probably that of the Lower Gravels at Swanscombe which was succeeded by the Middle Gravels at Swanscombe with an extinct species of *Microtus* and a lemming and was the equivalent of the Dutch Drenthian—both contain *Dama clactoniana* and a closely allied Clactonian flint industry.

The great interglacial is the period of stupendous fluviatile erosion in the Thames and Ouse and in East Anglia and the Midlands (see p. 1005). It preceded the Boyn Hill Terrace of the Thames.[347]

The Aurignacian caves of Cae Gwyn, etc., in north Wales may be Riss-Würm, though they also have been assigned to the Würm 1–2 interval by those who bracket the Older and Newer Drifts of south Wales with these horizons.[348] The third Welsh glaciation (see p. 774), like the Athdown glaciation on the other side of St. George's Channel (see p. 781), was later

SUCCESSION

Oxford and Upper Thames	*Lower Thames*	*Severn*	*Avon*	*West Midlands*	*South Wales*	*Cumberland*
Mammoth at base of channel	Slades Green Trail and Buried Channel	Welsh Re-advance Worcester T.		Welsh Re-advance		
Solifluxion Wolvercote Channel Northmoor T.	Ponders End trail Flood Plain T.	Irish Sea drift Main T.	No. 2 T.	Irish Sea drift	Newer drift	Main Glaciation
U. Summertown-Radley T.	*Clacton-on-Sea-Crayford Taplow T.*	*Kidderminster T.*	*No. 4 and No. 3 T.*		*Neritoides beach*	
Wolvercote T. Moreton drift	Main Combe-rock	Second Welsh drift	No. 5 T.	Welsh glaciation Great Chalky B.C.	Older drift	Early Scottish glaciation
Hanborough T.	*Ilford Boyn Hill T.*	*Bushley Green T.*		*Jurassic gravels*	*Patella beach*	
	Hornchurch B.C.	First Welsh drift Woolridge T.		Early Pennine ice First Welsh drift		B.C. of Silloth, Maryport and U. Caldew
Plateau drift (in part)	Winter Hill T. Older Drift: Pebble-gravel					

than the Irish Sea glaciation of the ice of the Newer Drift by at most an interstadial.

The formations along the south coast of England have been linked with the Alpine scale as follows[349] (although they do not agree altimetrically with the Thames terraces): Goodwood and Bembridge beaches, Mindel-Riss; *Patella* beach, end of Riss; Trebetherick blown sand and Barnstaple and Portland beaches, Riss-Würm; and Lower and Upper Head, Würm. The beaches of south Wales (see p. 1253) may perhaps be correlated as follows: *Patella* beach, Günz-Mindel, *Neritoides* beach, Mindel-Riss, Heatherslade beach, Riss-Würm. The *Patella* and *Neritoides* beaches have both been recently placed in the Mindel-Riss (D. Wirtz, 1954).

W. B. Wright[350] equated the deposits and glacial succession as follows:

Würm: Flood Plain deposits, trail and buried channel.

Riss-Würm: 15 m terrace of lower Thames—warm Mousterian.

Riss: Main Combe rock: York Line, early Levalloisian.

Mindel-Riss: 30 m terrace of lower Thames: Hoxne and other lake sites; Clactonian II and III and Middle Acheulian.

Mindel: Great Chalky Boulder-clay: solifluxion in Thames: Clactonian.

Günz-Mindel: 45 m terrace of lower Thames—Chellean of Breuil, Clactonian I and early Acheulian.

Günz: Plateau gravels. Pebble gravels.

P. Woldstedt[351] places the Kirmington, Corton Sands and lower warm beds of Hoxne in the "great interglacial"; brackets the Great Eastern glaciation with the Saale, and the Little Eastern glaciation with the Warthe, and refers the upper warm series of Hoxne and the March gravels to the last interglacial.

Since, apart from the Cromerian, there are two or three interglacial horizons, the correlation of these with the warm faunas of the caves[352] of Kirkdale, Settle and Raygill in Yorkshire and of Minchin Hole and Bacon Hole in Gower is, in the absence of palaeoliths, a difficult problem. Like the older terraces of the Trent,[353] they may belong to the "great interglacial", whose closing climatic worsening may be represented by the mammoths of Scotland and Ireland. M. A. C. Hinton,[354] however, has suggested that most of the British cave-deposits are intermediate in age between the late Taplow Terrace (Crayford stage) and the Ightham fissure stage—they contain reindeer and a number of arctic rodents. It will be observed that no member of the "warm" fauna has so far been found in either Scotland or Ireland.

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Chapter XXXIX

PLEISTOCENE STRATIGRAPHY: CORRELATIONS

1. General

Methods. Pleistocene correlations are difficult and uncertain; time divisions are short; glacial deposits are virtually unfossiliferous; interglacial accumulations, if fossiliferous, occur in isolated and discontinuous patches; animals and especially plants belong to genera and species still living; and essentially similar sequences of faunistic and floristic changes took place during each interglacial epoch. Nevertheless, many methods are now used to correlate drift successions within a single area or between narrowly or widely separated regions. Among the stratigraphical means are glacial erosion and deposition; loess horizons, often the backbone of glacial correlation; the degree of weathering of the drifts[1] where conditions of rainfall, stream-gradients, state of underground drainage, texture of the deposits and biological activity are comparable; the amount of erosion suffered by each drift[2] and the size of the intersecting valleys[3]; teleconnexions by varves, as those of Riss age in west Europe[4]; and associated terraces and marine deposits (see p. 1255). Volcanic material is also useful. Examples of this tephrochronological method are the Icelandic ash in Alleröd mud at Jaeren in Norway[5] and fossil pumice in the beaches of west Norway (see p. 1305); the ash zones in the cores of the North Atlantic,[6] in the Mediterranean[7] (including the raised beaches) and in Alberta and the Pacific North-west[8]; and the volcanic horizons in the Great Plains of North America (see p. 978), in the deposits of Patagonia and Tierra del Fuego[9] and the Argentine.[10] Pollen, as in the Mediterranean,[11] may also be occasionally used.

Palaeontological evidence is given by the succession of floras and of molluscan and mammalian faunas, owing to the appearance and disappearance of species, and by the sequence of palaeolithic cultures. All these may be checked by the relative extent of the ice-sheets in the various regions[12] or the distance to which they radiated[13] (see p. 1041).

The floras and faunas of the different interglacials were not completely identical. Thus the "great interglacial" between the Elbe and Vistula is characterised by *Paludina diluviana* and by *Hydrocotyle natans* and *Naias minor*, the last interglacial by *Zannichellia*[14] and by a *Brasenia-Trapa* flora[15] —it is said that *Brasenia purpurea*, distinguishable into two species *B. nehringi* and *B. shroeteri* and of early Tertiary descent, had an asylum in the west, especially France, in glacial time but died out during the last interglacial epoch. The interglacials are also distinguishable by their pollen (see p. 908): in north Germany, *Pinus montana* and *Picea omoricoides* were in the penultimate interglacial.[16] Similarly, the Yoldia clays differed among themselves (see p. 948). Thus the postglacial clays of Vendsyssel contain *Tellina loveni* and *T. torelli* which are absent from the Yoldia clays of the Skaerumhede series; the interglacial temperate fauna of this series has *Bela incisula*, an American form, which is missing from other horizons; and *Tapes senescens* of the Eemian is wanting from other beds in north-west Europe.[17]

These methods of attack, simple though they seem to be (others based upon included diatoms[18] are apparently impracticable), are in reality most difficult to apply; they have led to entirely different opinions. Thus the weathering of a single drift sheet varies considerably according to climate, topography and drainage.[19] For example, the drifts are more denuded on the flanks of the Juras than on the Swiss Plain; boulders in sandy or gravelly drifts are often markedly disintegrated, especially if of granite or mica-schist; and younger drifts may exhibit no trace of lime while older ones react vigorously.

Similarly, altimetric observations on glacial and interglacial sea-levels by no means conform to the simple eustatic scheme. Thus the North Sea glaciation in East Anglia coincided with a marine transgression of some importance and the interval between the North Sea and Great Eastern glaciations was one of uplift and not of submergence and aggradation (see p. 992). Furthermore, because of the relative shortness of the Pleistocene, the faunal evolution and extinction were not sufficient to yield the fine divisions which are essential to detailed correlation. This was particularly so in the tropics where the lowering of the temperature had little effect on the fauna and flora and where, as is exemplified by the discussion on the *Pithecanthropus* beds (see p. 858), the exact age of a deposit is difficult to determine.

Additional handicaps are introduced by the fact, which is becoming increasingly patent, that glacial maxima were not simultaneous but possibly proceeded wave-like over wide regions,[20] as is implied, for instance, in the hypotheses of migration of ice-centres and of sympathetic glaciations (see pp. 671, 677). The ice-sheets persisted too into times when the climate that called them forth had long since passed away (see p. 679). We can, indeed, scarcely doubt that the ice-masses, because they varied in size, altitude and climate, were not strictly contemporaneous: they began and disappeared at different times, and interglacial and postglacial epochs became shorter as the ice-centres were approached.

These difficulties, which singly or combined have raised doubts as to whether correlation is possible at all,[21] can only be overcome by careful field-work. Yet the time may be rapidly approaching when by the united efforts of glacialists, palaeontologists, biologists and archaeologists, a final subdivision of the Glacial period will be achieved. Compared with earlier geological periods there is a great wealth of information.

Terraces. Terraces, which have played a large part in these discussions, may be of several kinds.[22] They may be (*a*) tectonic, as possibly in the case of those of north Germany (see p. 1265) which have been linked with the depression of the crust beneath the ice and with the marginal bulge[23] (see p. 1349); (*b*) climatic,[24] like those in the higher reaches of valleys which were under the influence of the ice-sheets and their fluvioglacial streams, as in the Alps (see ch. XXII), or those in Europe's periglacial zone, e.g. Thames and Somme, Elbe and Oder (see p. 1267), which accumulated materials during glacial epochs, when rock-waste was plentiful and the rivers were somewhat low, and eroded during interglacial epochs; or (*c*) thalassostatic, i.e. dependent upon eustatic movements of the sea (see ch. XLIV). In general, the terraces were climatic in the higher parts of valleys, which were uninfluenced by tectonic movements or changes in sea-level, and thalassostatic in the lower parts of valleys, e.g. Thames and Somme and possibly in the lower Rhine.[25] In these parts, the gradient below the knick-point (which is slightly above the highest tides) is much steeper than that of the flood plain above it and the

deposits thicken and diverge downstream, their cold base passing upwards into warmer deposits. Above the knick-point, the terraces are climatic and parallel, the rivers aggrading during the cold periods and eroding during the warmer ones. It is the interplay of these factors which has made correlations in the Thames so difficult.

Most authors[26] refer the downward river-erosion to interglacial times, though some regard it as of glacial[27] or of lateglacial age.[28] Lateral erosion is placed in interglacial,[29] glacial[30] or lateglacial[31] times.

Loess horizons. The loess, which in China is apparently indivisible[32] (though three loess horizons are claimed for north China[33]), was in periglacial regions a product of the onmarch and maxima of the glaciations and was decomposed by the mild and moist climate and rich vegetation of the succeeding interglacial epoch (see p. 539). It occurs, in general, on two horizons of quite different age and somewhat different colour, the older loess being darker though not distinguishable palaeontologically. The earlier loess which, as in the Somme and in Germany, is divisible into two, corresponding to the twofold character of the Saale glaciation, is thoroughly decalcified; the newer one is altered only superficially. An older and a younger loess are known from various parts of Germany,[34] e.g. the southern margin of the North German Plain, lower Rhine valley and south Germany, and from Alsace, e.g. Achenheim[35] (9 km west of Strasbourg), Switzerland,[36] Bohemia,[37] the Somme and Paris basin[38] and Jersey[39]: they appear to be the rule in Europe. The loess of the Günz, like that of the Nebraskan in North America, if ever developed, is now so thoroughly eroded and poorly exposed that it is scarcely, if at all apparent. Nevertheless an ancient loess in the Rhône valley has been correlated with the Günz[40]—it contains a Villafranchian faunula[41] (see p. 539)—and Eberl[42] has described loess horizons connected with his Donau glaciation. Loess was associated with the Elster, Saale and Warthe glaciations, though most of the loess belongs to the last glaciation, the older loess occurring mainly in west and south Germany.[43]

Three loess horizons occur[44] in Baden and Thuringia, at Achenheim and Basle, and in Bessarabia, the Balkans and the Ukraine. Believers in four glaciations, each with its loess, recognise four horizons[45]; the youngest, indeed, has been subdivided to correspond to the "postglacial" stages,[46] and in north France[47] and parts of Germany (e.g. Upper Rhine, Swabia, Silesia) is twofold,[48] as was the last glaciation (see p. 1045), since a thin fossil soil, implying a relatively short climatic break, lies between them (see below). In occasional sections, e.g. at Wallertheim, Peterfels and Achenheim, in Czechoslavakia and in Lower Austria, the Younger Loess II is again subdivided by a thin weathered loam, suggesting that the last glaciation is divisible into three cold phases[49] (see p. 920)—the three ergerons of Belgium (lower, middle and upper) and the three loess horizons in the Seine have also been equated with Würm 1, 2 and 3[50]—while in France each of the two younger loesses has been subdivided into two[51]—the *argile rouge* belongs to the last interglacial. The last three loess loams of Austria (see p. 513) have been assigned as follows: Krems, Riss-Würm, Gottweig (Fellabrunn) and Paudorf, interstadial.

In all probability, loess was deposited under favourable conditions at or near the margin of each glacial age. Thus in the Ukraine five loess horizons have been correlated with glaciations, the first with a pre-Elster glaciation, the last two with two Weichsel maxima.[52] The loess horizons in the Vienna area have been assigned to the Mindel and Riss and Würm 1 and 2.[53] Yet the

loess of the Balkans has been referred to the Würm glaciation only[54]—the land was not sufficiently elevated to give loess horizons at earlier periods (see p. 653). The absence of loess from the two earlier glaciations elsewhere has been explained in various ways (see p. 539).

In the basin of the Rhine, e.g. at Achenheim and at Mauer, three older loesses are distinguishable, separated by loamy weathered horizons. The Middle Older Loess of Achenheim (see p. 539) at its base (*loess atypique*) contains a forest fauna, with, among other animals, *Elephas antiquus, Diceros merckii* and *Equus germanicus*, and is overlain by fresh loess representing possibly a cold phase in the interglacial separating the Elster and Saale glaciations to which the two older loesses belong.[55]

The various loess horizons in Germany are correlated as follows[56]: Younger Loess I and II with the two periglacial river-terraces of post-Saale date in Thuringia and the Warthe and Weichsel—the Weichsel drift has no loess upon it and the Warthe drift only one loess deposit. In Upper Silesia,[57] the Younger Loess can be traced south of the Brandenburg moraine and across the moraines of the Warthe phase and contains Aurignacian, Solutrean and Magdalenian implements. The Younger loess, which in south Russia is so thick that it veils the older deposits, in the Ukraine contains Aurignacian.[58] The Bulgarian loess horizons have been linked with the Riss and Würm 1 and 2.[59]

The North American loess is mainly associated with the Iowan[60] (= Peorian or Early Wisconsin) and extends over the weathered and eroded Kansan drift, over the marginal part of the Iowan drift, and on to the slopes and uplands of the Driftless Area and from western Nebraska to the Gulf of Mexico. It is, however, also known from each of the other glacial horizons; Aftonian loess occurs in few places; and Loveland loess, one of the greatest sheets and of Illinoian age, extends from west Kansas and Nebraska across Iowa and Illinois into Indiana. The older loesses were originally more extensive but were largely reworked and removed by erosion.

Palaeolithic cultures and climatic phases. Since Lyell[61] first examined the chronological relation of the palaeolithic cultures to the Ice Age and de Mortillet[62] attempted to establish the relationship, great advances have been made; as a monoglacialist, de Mortillet placed the Chellean in the preglacial, the Mousterian in the glacial and the upper Palaeolithic in the postglacial. Although, generally speaking, as Penck[63] showed in 1884, palaeolithic man lived outside the glacial limits, the glacial sequence provides a chronological framework for the cultures as M. Boule first showed in France in 1888.[64] Pre-Chellean and Chellean (Abbevillean) cultures, following Boule's demonstration, have been unanimously regarded as contemporaneous with a warm climate, the "Chellean interglacial"[65]—from this view few have dissented.[66] Chellean stations are open valley sites (*stations en plein air*), as on the Marne and Somme (see p. 1258); their *faune chaude* or "*antiquus* fauna"[67] of the "Hippopotamus Age"[68] comprises *Hippopotamus, Elephas antiquus, E. meridionalis* and *Diceros leptorhinus*. Chellean alone of the cultures is unconnected with loess though it is said to have been associated with steppes towards the south.[69] Like the Acheulian, it was probably a forest culture.

There is also a concensus of opinion[70] (a few dissent[71]) that the Acheulian was in the main interglacial: Chellean and Acheulian in many river-gravels are intimately associated; the technique of flaking changed gradually since the

Abbevillean is best regarded as merely the earliest phase of a single Abbevillean-Acheulian culture; no faunal break occurred; and a warm climate continued during the two phases,[72] e.g. in the Pyrenees, the Somme (see p. 1258) and the Thames. Almost all the stations are open—cave sites with Acheulian implements do however occur in France and Palestine—and the fauna, save in more northern latitudes where mammoth and woolly rhinoceros are included, consists of the southern trio and other warm animals.[73] Only with Breuil's Acheul stage IV did the climate begin to grow cold and culminate in the glaciation of stage VI[74]; the loess at Achenheim, for instance, contains a younger Acheulian industry (see p. 1036). This view is supported by the lower terrace of the Somme[75] and the St. Acheul workshop site at Whitlingham in the Yare valley, Norfolk.[76]

The Mousterian, on the other hand, straddles a glaciation as G. de Mortillet suggested in 1880—he equated it with the single glaciation then accepted—and is proved by the cold fauna at Le Moustier and La Quina. It was the "mammoth period",[77] with mammoth, woolly rhinoceros, cave bear, reindeer and the microfauna of the lower rodent layer (see below) which replaced the *faune chaude*. It was contemporaneous with the First Younger loess and Würm 1.[78] Nevertheless, Hřdlicka[79] thought the climate was not very severe for fully two-thirds of the stations are in the open and of the remainder quite a few, e.g. Krapina and La Ferrassie, are in or about rock-shelters which offered little protection from the cold. The progressive mental and physical change of Neanderthal man and the morphological variability of his remains show that it was a time of stress.

There was, however, a "warm Mousterian"[80] or "Micoquean" with early Levalloisian implements, which it is said followed[81] but certainly preceded[82] the "cold Mousterian", e.g. the Levalloisian VI–VII at Montière near Amiens, Crayford, Baker's Hole, Northfleet and the 120-ft terrace of the River Stour.[83] Its "second *antiquus* fauna",[84] a recurrence of the interglacial fauna, comprised *Elephas antiquus* (recent form) *Diceros, merckii*, cave lion, cave bear, cave hyaena and other animals as the lignites of Dürnten and the travertine of Weimar and Cannstadt suggest[85] (even three "*antiquus* faunas" have been postulated[86]). The warm phase was widespread[87]: it is seen in the tufas of Taubach and Flüringen, the lignites of Wetzikon, and the river-gravels or cave-deposits of the Somme, upper Thames, Ehringsdorf, Krapina, La Micoque, Laussel, La Ferrassie, Cotencher, Wildkirchli, Drachenloch, Grimaldi, Monaco, Mentone, near Rome and in south Italy. Boule and others assert that the fauna, as in the French caves, remained cold between the Mousterian and Magdalenian and that a warm period after the Mousterian is illusory[88] (see below).

Nevertheless, it is contended that there is only one "*antiquus* fauna"[89]; that warm species, like *Diceros merckii*, on this horizon are derived[90]; and that the warm phase is not found in the Somme[91] or north but only in a "warm province"[92] which embraced Spain, Italy, Mentone, Grimaldi and Monaco.

It is important to remember, as is generally recognised for North America, that latitude influenced the range of Pleistocene animals and, as Commont observed, provided zoological provinces. For instance, Italy was forested when central Europe was a tundra (see p. 1379), and tundra in Scandinavia during the final recession was contemporaneous with forest farther south. The Mousterian was coeval in north Italy and the Pyrenees with a cold

fauna[93] (mammoth, reindeer), in the Apuan Alps with one warm species (*Diceros merckii*), and in the "thermal gulf" of Grimaldi and south Italy with a true warm fauna[94]—Neanderthal man was associated at Rome with a warm fauna[95] (*Elephas antiquus*, *Diceros merckii*, *Hippopotamus*)—which persisted without any cold admixture into upper palaeolithic time in the Mediterranean islands. About Otranto and Italy's southern extremity the cold fauna of the cold trio and the great auk, *Alca impennis*, is restricted to the upper Palaeolithic. This fauna failed to penetrate into Portugal[96] or into Palestine[97] or Algeria[98] though cold-loving birds, e.g. *Montifringilla nivalis*, *Octocoris penicillata* and *Pyrrhocorax alpinus* lived in Lebanon[99]: this agrees with the Mousterian sites *en plein air* in Tunisia and Morocco and in north-west Africa generally.[100]

Elephas antiquus survived into the Aurignacian at Taubach and Krapina, and in south France and Italy into the Würm glaciation[101] and the marine *Strombus* horizon.[102] *Diceros merckii*, which usually outlived *Elephas antiquus* and *Hippopotamus*,[103] persisted into upper Mousterian[104] in the Pyrenees and at Grimaldi and Monaco, and a warm fauna lived throughout the Ice Age in south Spain, with *Macacus tolosanus*, and in the coastal zone of Cadiz and Malaga where solifluxion soils or other signs of a cold climate are wanting.[105] The mammoth only arrived in early Mousterian time in Catalonia and Cantabria and in the Solutrean of Gerona and Asturias[106] which was temperate in the south.[107] The *Hyaena striata* group, which lived in England, central France and central Germany in upper Pliocene and lower Pleistocene times, was shifted to south France and Lower Austria in the second interglacial and to Italy and Portugal in the third interglacial.[108]

Evidence from the upper Pleistocene in the Mediterranean (Grotte de l'Observatoire, Monaco, Grimaldi caves, coastal plain of Lower Versilia, Pontine Marshes, Grotta Romanelli, Mount Carmel) suggests, it is said,[109] that after the warm Mousterian sea there occurred three cold phases of the last glaciation, of which the third was the weakest and humid everywhere and cool north of 42° N. and the second the most intense, the latter having a first humid subphase and a subsequent cold and mostly dry subphase.

These observations suffice to prove, as was only to be expected, that latitude influenced mammalian distribution; the climatic phases and faunal succession of central Europe did not extend into Mediterranean lands.

The Aurignacian was glacial[110]; some equate it with the maximum of the last glaciation.[111] It had arctic molluscs[112] and lies between the two rodent layers, Mousterian and Magdalenian in age, e.g. at Sirgenstein, Wildscheuer and Ofnet, while its cold mammals ranged as far south as the Côte d'Azur, Pyrenees and Dordogne[113]; it contains glutton in Swabia and musk ox on the Vézère, Lahn and Danube[114] (Krems). *Abies alba*, *Pinus excelsa* and *P. sylvestris* grew in north-east Rumania[115] and Aurignacian caves and shelters existed even in south France.

Yet there was a slight amelioration.[116] Thus the stations of human occupation were more frequent in the open country and had tents and log shelters (to judge from the "tectiforms" of wall diagrams). The mammalia were mainly steppe animals, namely, saiga antelope, cave lion, cave bear stag, roebuck and abundant horse ("horse epoch"[117]), reindeer being less common than in the following Magdalenian stage. Aurignacian man is not found close to the ice-edge but 200–500 km from it as in Stuttgart, Moravia and Lower Austria. Plants provide further evidence of this improvement.[118]

The Solutrean was less genial. Its glacial climate is shown by the fact that this culture exists nowhere within the last Alpine glaciation nor in the Pyrenean glacial valleys,[119] by the animals[120]—reindeer ousted horse—and by *Larix polonica* and *Pinus cembra* in Poland.[121]

The Aurignacian and early Solutrean correspond to the steppes[122] of either an interglacial or an interstadial epoch,[123] Bayer's "Aurignacian oscillation"[124] (Riss-Würm, Würm 2–3[125]) or is now generally thought Würm 1–2, during which even in Bayer's opinion the Scandinavian ice withdrew into north Sweden and Norway. Yet Europe nowhere had a warm fauna at this time, except at Castillo[126] in Spain, which had two reindeer horizons. On the contrary, the cold *primigenius-antiquitatis* fauna persisted from Mousterian to Magdalenian,[127] as in Russia and south Germany, e.g., at Sirgenstein, though the rodents temporarily disappeared after the lower Aurignacian, re-appearing only as the last glaciation moved towards its climax in early Magdalenian time (Würm 2). The cool and dry climate favoured the open life of the Solutrean and led, possibly, to the suspense of the cave art.[128] Lower Aurignacian (Châtelperron) in Palestine appeared after the first phase of the last glaciation[129] and the middle and upper Aurignacian in Europe lasted into the second cold phase.

The fact that the mammalia of the last interglacial and last glacial epoch do not differ markedly may be explained by the great range of modern mammals,[130] e.g. deer in Europe (10°C difference), elephant in India and Africa (15°C difference) and reindeer in North America (30°C difference). As the climate worsened, horse replaced elephant and reindeer the horse, since one elephant requires the space of 15 horses and one horse that of three reindeer.[131] The inundation by the cave bear during the *Ursian* (see pp. 819, 1035) was related to the improvement in its environment and the expansion of its living space. The same was true of the reindeer at the close of the last glaciation and of the lemmings towards the end of the Glacial period (see below).

The maximum cold was not necessarily coeval with the maximum precipitation nor with the greatest expanse of the ice,[132] though this has often been assumed.[133] Maximum glaciation at each epoch may have lagged behind the maximum severity of the causal climate.[134] In any case the last glaciation seems to have been the coldest[135] and the longest[136]—the steady uplift (see p. 653) may have had something to do with this, or, alternatively, the cooling of the oceans by repeated additions of cold melt-waters.[137] Thus the mountain glaciations south of the ice-sheet, e.g. in the German Mittelgebirge, Steier Randgebirge, Apennines, Balkans, Spain and Portugal in Europe, in Persia, Asia Minor and the Caucasus, in the Atlas and in North America, belonged to the last glaciation,[138] as did that in Richthofen Mountains, central Asia, to judge by the freshness of the drift or height of the snowline—the absence of glaciers from the German Mittelgebirge at the earlier periods has been correlated with the dry periglacial influence, with a different climate, and with later earth-movements (see p. 653). At this time, the erratics were drifted along the English Channel[139] (see p. 1097); the caves were chiefly occupied by glacial animals[140] in Europe and the Mediterranean, and the cold animals ranged farthest south,[141] e.g. *Dicrostonyx torquatus* and *Citellus rufescens* in Hungary, south-west France and the Pyrenees, *Gulo luscus* in Switzerland, *Rangifer tarandus* in south Europe (see p. 806), reindeer with snow-hare and polar birds (*Buteo lagopus, Otocaris alpestris*) and flora (poplar, birch, willow and juniper) in the Crimea[142] and alpine steppe forms, e.g. ibex

and hare, in the cave of Romanelli, Otranto.[143] *Pinus sylvestris* probably reached the Portuguese coast at this time (see p. 1032). Saxony had then only a thin animal population, animals and man having retreated to more sheltered Bohemia.[144] *Cyprina islandica* occurred in Castillo cave, Pyrenees (see p. 1090). It is Osborn's "Ovibus zone" in North America (see p. 821).

There was a marked change in the late-Pleistocene mammalian faunas of Europe (see p. 817), of Palestine[145] (where the three Würm stages had their influence) and India (see p. 822) and in East Africa (between Upper Kamasian and Gamblian) where the lower fauna was Asian in character.[146] In these cases, the extermination of the older fauna has been connected with earth-movements, viz. rifting in Africa, folding in Asia. Species of *Dulichium* disappeared at this date,[147] as did the warm animals which survived the early glaciations (see p. 816), e.g. in the Somme,[148] and the dwarf elephants of the Mediterranean islands.[149] Moreover, loess is absent from the glaciations which preceded the "great interglacial" (see p. 539) and Spain was first isolated as a separate region of evolution after the Aurignacian.[150] The fact that the Glacial period influenced the mammalian life only towards its close and that only one sharp faunistic line occurs in Europe, Africa and India has led some mammalian palaeontologists to regard the glacial curve as single (see p. 913); during the earlier epochs the climate was more equable or oceanic.[151]

The Magdalenian was the "reindeer period" (see p. 815) as the rival views of Penck and Boule alike affirm (see below). The extreme cold is testified to by the fauna, known from bones or from engravings, carved figures and paintings in Magdalenian caves—it consisted of reindeer, musk ox, glutton, lemmings (upper rodent layer), arctic hare and horse (in greatly diminished numbers)—as well as by the widely distributed *Dryas* flora of north-west Europe which in the clays of the glacier-lake of Havelland in Brandenburg occurs with Magdalenian harpoons.[152] Arctic plants were also associated with the Magdalenian station of Schussenquelle,[153] and the stations of Kesslerloch and Schweizersbild are younger than the Singen phase and possibly (though this is contested) than the Constance phase.[154] The arctic fox was then most widely distributed in Europe, *Lagopus lagopus* extended as far south as Hungary and the Dordogne, and cave bear degenerated and became smaller in size (see p. 800).

This climatic pessimum is also suggested by the fine needles and other implements of this kind and by the percentage of palaeolithic sites in the open and in caves as is set out in the following list[155]:

Period	*Sites in the open*		*Rock-shelter or cave*	
	No.	*Per cent*	*No.*	*Per cent*
Pre-Chellean	11	100	—	—
Chellean (Abbevillean)	32	94	2	6
Acheulian	36	78	10	22
Mousterian	45	34	88	66
Aurignacian	24	18	112	82
Solutrean	10	14	62	86
Magdalenian	17	10	148	90
Azilian and Tardenoisian	4	9·5	38	90·5

Caves tended to be inhabited at any time where available, e.g. by Azilian man in south France and north Spain, by Tardenoisian man in central France, south Germany, Belgium and Great Britain, by Obanian man in west Scotland, and by the hunter-fishers of Viste near Stavanger. Yet Magdalenian man to judge from the tectiform designs had summer dwellings in the open,[156] e.g. the Hamburgian and, to judge from designs, in the Dordogne, and certainly had in south Russia where in the absence of caves man lived in tent-like structures or earth-houses on river-banks.[157]

In view of all this it is perhaps not surprising that the Skaerumhede interglacial series (see p. 950) had not the warmth of the previous interglacials. Timber played but an insignificant role in the economy of the upper palaeolithic hunters of France and England: the equipment lacked the axe and was adjusted to life on treeless steppes or tundras. This last interglacial was less protracted, had a fauna which comprised both cold and warm forms and contained a subarctic phase in the middle part of it[158] (cf. p. 951).

The climate was highly arctic during the early Magdalenian only. Certain evidence, e.g. in the Rome and Pisa areas and about Lago di Garda, suggests that the climate during Würm 1 times was cold and moist and became cold and continental in Würm 2 times.[159] The climate ameliorated towards the close of the period as the south German caves show,[160] though Kesslerloch (see p. 789) and Peterfels in the Lake Constance area prove that Magdalenian persisted into Würm 3.[161] Mammoth, woolly rhinoceros and cave bear had died out in France and Swabia by the full Magdalenian[162] (the time when *Ochotona pusillus* appeared) or the upper part of the upper rodent layer (Kesserloch shows that a few individuals survived on the northern Alpine slopes[163]) though reindeer persisted until later (see p. 819). Reindeer's place was usurped by the stag, *Cervus elephas*, which was not fitted like the reindeer with broad hoofs to run quickly over yielding crusts or through deep snow.[164] Aurignacian flint implements, e.g. keeled grattoir, pedunculate point and points recalling those of Abri Audi and La Gravette, re-appeared[165] and the Capsian peoples migrated northwards.

The Azilian falls into the period of the forests[166]—the arctic flora had vanished—and the Azilio-Tardenoisian of the Pennine Chain into the Boreal period.[167] The abundant miniature implements of the Tardenoisian suggest that wooden clubs or spears were used and that timber was already more plentiful.[168] In Russia, as in Britain (see p. 1014), the palaeolithic stations lie outside the limit of the last glaciation but mesolithic stations lie within it.[169]

Alpine equations with cultures and mammalia. Before the Glacial period's complexity was realised, palaeolithic man and the contemporary animals were referred to either a preglacial[170] ("antidiluvian") or a postglacial age[171]: the monoglacialist in general still adopts one or other of these views.[172] The recognition of genial epochs has introduced a wide diversity of opinion which reveals both the difficulty of the subject and the need for prudence. It is indeed contended that palaeolithic cultures cannot be used as "zone fossils"[173] and the geologist must date the cultures in a given area for the archaeologist rather than vice versa. Almost the sole features common to the various classifications are the equation of the Magdalenian with the final cold of the Ice Age and of Chellean (Abbevillean) with an interglacial epoch, regarded as Günz-Mindel[174] by the authors of the longest chronology but usually as Mindel-Riss[175] or occasionally as Riss-Würm.[176] The first

correlation, challenged on physiographic and other evidence,[177] is said to be sustained by the association of *Machairodus*, *Dicerorhinus etruscus* and *Equus stenonis* with the "Chellean fauna" at Torralba and Abbeville, by the derived Chellean hand-axes in the base of the Cromer Till and Cromer Forest Bed (see p. 1016), frequently placed in the first interglacial (see p. 1015), and by the fact that at the type locality it overlies what is probably a Günz solifluxion gravel.

Favouring the equation with the Mindel-Riss in the "long chronology" of Penck and many German glacialists and archaeologists are the absence of Chellean on Riss terraces and of Acheulian on the *Hochterrasse*; the restriction of the Mousterian (Levallois) localities, e.g. in the Somme, to areas outside the Riss glaciation—whence it is concluded that the Mousterian culture coincided with this glaciation and the Magdalenian culture with a post-Würm age; and the occurrence of the Acheulian in a schotter beneath the ground-moraine of the German Saale glaciation.

The reference of the Chellean to the Riss-Würm, i.e. one stage further forward, is usually associated with Boule who propounded it in 1888 and with the French school of archaeologists who have modified de Mortillet's view of 1883, replacing his preglacial by the last interglacial and his Glacial period by the last glaciation. In its favour—it correlates Mousterian with Würm (those who put the Chellean in the Mindel-Riss and the Acheulian in the Riss-Würm also arrive at this conclusion[178])—are the Acheulian *bouchers* on the Riss moraines of Switzerland,[179] e.g. at Challes de Bohan and Lebrun near Conliège, and in the third terrace of the Pyrenees[180] (see p. 938); the direct contact of the Würm (or Néowürm) moraines[181] with the Mousterian in the Swiss Jura, as at Cotencher[182] (659 m) in the Neuenburg Jura (= Riss-Würm) and with Solutrean at Kesslerloch; and the presence of Mousterian in the lower (Würm) terrace of the Pruth[183] and in Mediterranean deposits of the last glaciation[184] in the Pontine Marshes, in Lower Versilia and in the caves of Grimaldi. Militating against it is the compression of the whole evolution from the crude Pre-Chellean to the fine Micoquean into the short space of the Riss-Würm. There is now general agreement among European prehistorians that the Micoquean ("warm Mousterian") belongs to the Riss-Würm and the cold Mousterian to the Würm. The main differences between the two schools of long and short chronology (see p. 1033) concern the relative date of the Chelleo-Acheulian succession.

Correlation is difficult because palaeolithic sites are rarely in direct contact with glacial deposits that are definitely dated. Palaeolithic man, as seen in maps of German palaeolithic stations,[185] was generally excluded from the glaciated territories, particularly those of the last glaciation. This is also generally true of Britain,[186] the Vosges[187] and Switzerland,[188] though the palaeolithic sites of Wildkirchli, Drachenloch and Wildenmannlisloch with their fauna[189] of *Ursus spelaeus*, *Felis spelaea*, *F. pardus*, *Cuon alpinus* var. *europaeus*, *Canis lupus*, *C. vulpes*, *Meles taxus*, *Mustela martes*, *Foeterius ermineus*, *Capra ibex*, *Rupricapra rupricapra*, *Cervus elephas*, *Marmota marmota*, *Lepus variabilis*, *Microtus nivalis*, are within the limits of maximum glaciation and are placed in the Laufen oscillation (W1–2),[190] or in an interglacial epoch, Riss-Würm[191] or Mindel-Riss,[192] the last made probable by the great altitude of the snowline during this period (see p. 917). The milder period is suggested by the cave panther which is generally found at considerably lower altitudes.[193] The treeline was probably 300–400 m higher

than now.[194] Wildkirchli was 200 m above the surface of the Würm glaciers descending from the Säntis, the dark fossil-bearing interglacial horizon (which owed its dark colour to the humus derived from interglacial plants) being sandwiched between light-coloured sterile loams formed during the glaciations when there was no vegetation.[195] The cave sediments were purely local in character and lacked erratics or other foreign material. There is no evidence that, as has been suggested, the great height of these caves is due to later earth-movements.[196] Man probably selected these high sites because they offered him a view over his hunting district better than did the lower, close-wooded region, and because the higher district was more prone to have game and because it provided corries and similar places where the fauna could be more readily hunted.[197]

The "alpine Palaeolithic", as E. Bächler[198] styled the atypical Palaeolithic of the Alpine stations of Wildkirchli (hence "Wildkirchli culture"[199]), Drachenloch, Wildenmannlisloch, Treis, Cotencher, Welden, Steigelfadbahn (Rigi) and Drachenhöhle, all on the northern side of the Alps, has uncertain relationships with the plain cultures: the implements are of quartzite, jaspar, hornstone and other atypical material. It may have arisen in the mountains, as an independent lower palaeolithic industry,[200] or as a primitive culture associated with the collective hunting of cave bears (*Höhlenbärenjägerkultur*, L. F. Zotz[201]) which gradually descended as the climate ameliorated and amalgamated with the typical upper palaeolithic cultures.[202] Alternatively, since it has also been found[203] at Petershöhle (K. Hörmann) near Nuremberg, in Bohemia (H. Franze), Moravia (K. Absolon), Steiermark (G. Kyrle), Silesian Sudetes (L. F. Zotz), Tuscany (R. Battaglia), Jugoslavia (S. Brodar) and in the Polotschnik cave on Karawanken at 1700 m (see p. 790), i.e. on most central European mountains, as well as in Rhine Hesse and Alsace,[204] it may have wandered in from Eurasia.[205] This is the epoch of the cave bear of E. Lartet (see p. 815). While Penck spoke of a true inundation of cave bear (*Höhlenbärenüberschwemmung*) arising from natural causes (see p. 790), and others attributed the abundance to a *Höhlenbärenjägerkultur* or "protolithic *Knockenkultur*", W. Soergel[206] maintained that the layer with bear remains was accumulated over an extremely long time of at least 6000 years in Würm 1–2, a figure M. Schlosser raised to 42,000–80,000 years.[207] Soergel with others[208] asserted that the remains were due, not to man's activities, but to natural causes, e.g. illness or old age; their date ranges from Pre-Mousterian to Magdalenian.[209]

The Magdalenian followed the recession of Aurignacian and Solutrean times (see p. 1030) and synchronised with the Würm[210] (or Würm 1) or with the Bühl[211] or Würm 2,[212] the Aurignacian falling into the Achen oscillation. Its implements near Schaffhausen, for example, occur in the two stations[213] of Schweizersbild (of Bühl age) and of Kesslerloch which was somewhat earlier—it lies within the Singen phase of the Rhine Glacier (see p. 1161), probably in the Constance phase of W. Schmidle, i.e. a phase of the "Lake Moraines" of Gams and Nordhagen.[214] The two cold layers (with Magdalenian) at Kesslerloch probably correspond to the Schaffhausen (Würm 1) and Singen (Würm 3) stages[215] (see p. 1161). Magdalenian occurs within the Würm moraines in other localities,[216] e.g. along the Rhône at Veyrier,[217] Scé (see below), Les Hôteaux, La Bonne Femme, Le Balme, and at Schussenried and Münzingen. The grotto of Scé[218] on Lac Léman, a witness of the first order, proves that the Magdalenian finished during an extremely

late phase of the Würm, most probably after the Bühl stage—it is younger than the Interlaken stage. Magdalenian man ranged as far as the mouths of the Alpine valleys and outlived the mammoth in Switzerland,[219] though this animal (with the woolly rhinoceros) is found at Veyrier and Scé and alone near Innsbruck and near Kufstein and very occasionally in other Alpine valleys.[220] Sites of Magdalenian 6 occur near Geneva, 3–6 in the Jura, 4–6 near Schaffhausen[221]—in the Pyrenees, Magdalenian 4–6 occurs at Lourdes, Niaux and Ussat.[222] In north Germany, the reindeer hunter's camp of Meiendorf near Lübeck Bay, the starting-point of the whole subsequent prehistory of north Germany and south Scandinavia, is well within the Weichsel glaciation (see p. 880).

Loess and cultures. The older of the two loess horizons generally recognised (see p. 1027), the *limon hesbayen* of Belgium, is younger than the Chellean, as at Sangatte[223]; it is Acheulian V at Achenheim[224] and in the Somme valley[225] where older loess rests on terraces 2 and 3 and upper loess on terraces 1, 2 and 3 (see p. 1258).

The Younger loess[226] has Acheulian VII, Mousterian and Levalloisian V in its lower division and in the upper ones mostly implements of Aurignacian or "loess man". It is widespread in Europe,[227] e.g. the *ergeron* of the Somme, at Ratibor in Upper Silesia, at Gronau in Hannover, in Lower Austria (along the Danube between Vienna and Melk, at Krems and Thiede, and at Brünn in Moravia), in the Rhine valley (Mettnich, Rhens, Unkelbach, Kärlich, Achenheim) and in the upper brickearths of the Thames valley. Yet loess conditions continued backward in a few places into the Mousterian,[228] e.g. at Achenheim and forward into the Solutrean,[229] as at Předmost in Moravia and Cannstatt in Württemberg, and less certainly into Magdalenian,[230] as at Andernach (= in loam above the loess[231]) in Upper Silesia,[232] at the "reindeer station" of Münzingen (Baden), at Gobelsberg (Austria) and at Gagvar (Hungary). These occurrences have led certain writers to correlate the upper loess with the Aurignacian and Solutrean[233] and the Magdalenian,[234] though others believe these upper palaeoliths are Gravettian and Aurignacian.[235] The "recent loess" of central Europe may not have begun on a grand scale until loess formation had almost ceased in the west.[236]

The late-Acheulian loess accumulated during the onset of the Mousterian glaciation,[237] the upper loess during the upper Levalloisian and "cold" Aurignacian oscillation or the advance of the Solutrean-Magdalenian glaciation, its two divisions corresponding to the first and second phases of the last glaciation.[238] Loess was not associated with the glaciation, whether simple or twin, which preceded the "great interglacial" (cf. p. 1027) as Penck and Brückner recognised for the Alps. Since the twin glaciations of the upper Palaeolithic are Riss and Würm, the Mousterian may straddle the Riss and the later cultures the Würm glaciation[239] (see below), alternatively Würm 1, 2 and 3.[240]

Rodent layers. The lower rodent layer which is widespread in north and south Germany,[241] e.g. Brunswick (Thiede), Swabian Alb (Sirgenstein), along the Rhine and Danube, and in Austria (Předmost), Belgium,[242] Jersey[243] and England[244] (Creswell), contains among other forms *Myodes obensis* and *Dicrostonyx torquatus*. Sirgenstein shows it to be Mousterian.[245]

The upper rodent layer,[246] found for instance at Sirgenstein, Wildsheuer,

Ofnet, Hohlenfels, Schussenquelle, Andernach, Kesslerloch and Creswell, probably belongs to the Magdalenian[247] and the Baltic Moraine[248]: its *Elephas primigenius, Rangifer tarandus, Ursus spelaeus, Dicrostonyx torquatus, Foeterius erminea, F. nivalis, Alopex lagopus, Sorex pygmaeus, S. vulgaris, Talpa europaeus, Lepus variabilis, Arvicola agrestis, A. amphibius, A. gregalis, A. ratticeps, Lagomys albus, L. alpinus* and *L. pusillus*, are associated with early Magdalenian implements.[249] Like the lower rodent layer it is absent from France, though the remains of some of the animals have been found.[250]

The glacial character of the fauna in the layer between the two rodent layers is less pronounced. For example, *Myodes obensis, Dicrostonyx torquatus* and *Alopex lagopus* disappeared from Sirgenstein and *Felis catus* and *F. lynx* point to wooded conditions.[251] Even reindeer is missing from Ofnet.

The two rodent layers in the opinion of most writers represent two glaciations, viz. Riss and Würm,[252] Würm and Bühl[253] or Würm 1 and 2.[254] This is essentially the view of those who bracket the two layers as the product of one cold period[255] if we postulate an oscillation of less than full interglacial rank. The rodent layers may, however, have no particular chronological value.[256] Alternatively, the lemmings may have wandered not in colder but in milder periods which, by favouring greatly increased numbers, extended the bounds of the species as they do to-day[257]—this is perhaps difficult to reconcile with the varied cold fauna found in the Markenstein Cave[258] east of the Alps and with the great thickness of the rodent layers which demand hundreds of years for their formation.[259]

Correlations. As a working hypothesis,[260] the Abbevillean (Chellean) may be correlated with the Günz-Mindel, the Acheulian and Clactonian with the Mindel-Riss, the Micoquean with Riss-Würm, and the Aurignacian to Magdalenian with the later phases of the Würm glaciation up to Würm 3. A fuller classification is as follows:

Palaeolithic Cultures and Glacial Succession

Würm 2	Magdalenian			
	Solutrean			
	Aurignacian		Levalloisian VI–VII	
Würm 1		"Cave Mousterian"	„ V	
R.-W.	Micoquean		„ III–IV	Tayacian II
	Acheulian VI–VII			
Riss	„ V	Clactonian IV		
	„ III–IV	„ III		
M.-R.	„ II	„ II	„ I–II	„ I
	„ I–II	„ I		
Mindel		„ I?		
G.-M.	Abbevillean	„ I		
Günz		Ipswichian		

This agrees with the evidence of the French terraces (see fig. 206) which, unlike the Thames terraces that lay in the tundra zone just outside the ice-sheet and its drift, are associated with loess deposits and, unlike the central European terraces (see p. 1267), have a cold horizon at the base and a warm facies in the upper part of each terrace. Breuil and Koslowski,[261] who

regarded the 55-m terrace of the Somme (see p. 1258) as preglacial, place the lower part of the 40-m terrace with Abbevillean I and Clactonian I in the Günz-Mindel interglacial and its upper part with the 30-m terrace and lower gravels of the 10-m terrace, containing together Acheulian I–IV, in the Mindel-Riss interglacial. The fauna and implements of the glacial epoch of down-cutting from the 40-m terrace are in their opinion unknown. It is probable, as H. Breuil himself later recognised (see below), that the Levalloisian should be equated with both the Riss and the Würm.[262]

The greatest glaciation (Riss 2) is represented by the ancient loess with mammoth fauna and Acheulian V culture, while the gravels on the edge of the 10-m and 5-m terraces with *Elephas antiquus* and *Hippopotamus* and Acheulian VI and VII (Micoquean) and Levallois III–IV belong to the Riss-Würm, Levallois V, found in the lower half of the "recent loess", belongs to the early part of the last glaciation (Würm 1) and the late Levallois VI and VII, Aurignacian, Solutrean and Magdalenian to its second phase (Würm 2).

The solifluxion nappes,[263] four in number, descend from the plateau on to these terraces and river-deposits. The lowest nappe (S1) rests upon the 45-m terrace and represents the first (Günz) glaciation. The second nappe

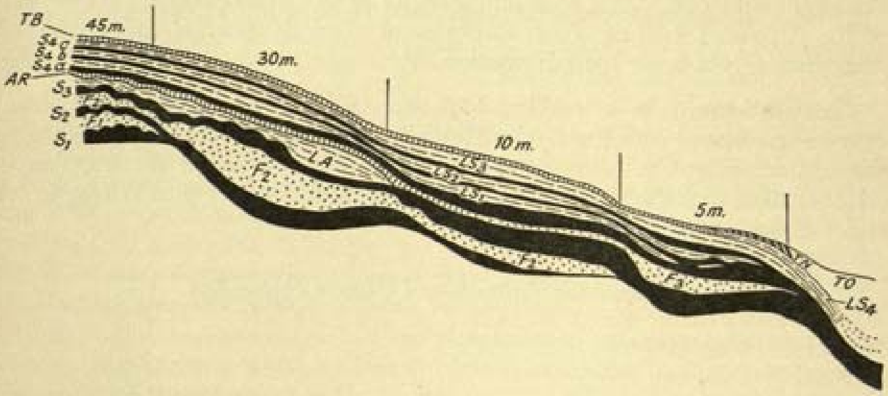

FIG. 206.—Diagram of the Somme terraces showing the relationship between the successive solifluxion nappes S_1, S_2, S_3, S_4a S_4b, S_4c and fluviatile deposits of the High Terrace, F_1, of High, Middle and High Lower Terraces, F_2, and of Lower Terraces, F_3, and of the loess LA, LS_1, LS_2, LS_3, LS_4, and the alteration loams AR and brickearth TB. TO = peat, TN = blackearth. H. Breuil, *R. Gg. phys. G. dyn.* 7, 1934, p. 272.

(S2), which contains abraded Chellean (Abbevillean) or Clactonian and belongs to the second (Mindel) glaciation, overlies the 45-m terrace and descends thence to the floor of the 30-m and 10-m terrace. The third nappe (S3) comes down from the plateau to the floor of the 5-m terrace and into the buried valley; with its derived Levallois I–II and cold fauna (mammoth, woolly rhinoceros, reindeer) and its cover of ancient loess with Acheulian V, it corresponds to the third (Riss) glaciation. The fourth nappe (S4), which encloses remains of the above-mentioned cold animals and descends right into the buried valley, is of Würm age and is overlain by the younger loess.

H. Breuil[264] in a more recent classification based on the longest chronology correlates the successive industries in Europe as follows:

Glacial Succession	*Bifaced Industries*	*Industries with wide and very oblique striking platforms*	*Flake Industries*	*Races*
Würm 2			Magdalenian Solutrian	*Homo sapiens*
W. 1–2			Levalloisian VI and VII and Aurignacian	
Würm 1			Levallois V and Mousterian	
R.-W.	Final Acheulian and Micoquean	Upper Micoquean Mid-Tayacian	Levalloisian IIIB and IV and Mousterian	Neanderthal
Riss	Preceding implements derived.			
M.-R.	Acheulian	Lower Tayacian Mid-Clactonian and evolved Clactonian	Levalloisian I, II and IIIA	Swanscombe
Mindel	Preceding implements derived.			
G.-M.	Abbevillean	Base of Clactonian		Mauer
Günz				

The relationship of the European cultures of the Palaeolithic to the *Vollgliederung* and Milankovitch's scale is given in the fig. 207 (after F. E. Zeuner[265]).

2. Correlations

(*a*) *Alps and North Europe*

General. The obstacles surrounding the correlations of the Alpine and Scandinavian successions are so formidable that all attempts must be deemed provisional. It has, indeed, been stated that the climates of the two regions were different[266] (the Alpine "great interglacial", it has been contended,[267] coincided with the major glaciation in north-west Europe) or that the Alpine glaciations, being smaller and more southerly and affected by different nourishment and radiation, were more susceptible to climatic changes and registered more of them.[268] The Günz glaciation, for instance, if ultimately proved for the Alps (see p. 937), may have been merely a local incident[269] and, as held on astronomical grounds, of short duration[270]; for an equivalent, though probable, has yet to be definitely discovered in north-west Europe[271] (cf. p. 941). On this view, the three glaciations of north-west Europe correspond with the Mindel, Riss and Würm[272]—the correlation of Würm and Weichsel has never been questioned. Those who recognise four Scandinavian ice-sheets, either a Pre-Elster or an independent Warthe glaciation, have a ready solution in equating these four with the classical Alpine four.[273] The "great interglacial" of the Alps is naturally bracketed with the Elster-Saale interglacial which caused deep weathering of the Elster drift and saw an extraordinarily large downward cutting of almost all German rivers,[274] e.g. in the Rhine, Elbe and Leine.

TIME SCALE	RELATIVE CHRONOLOGY	WEST AND CENTRAL EUROPE C	F	B	NORTH. MEDITERRANEAN C	F	B
				MESOLITHIC			MESOLITHIC
25000	LGl_3			PRE-TARDENOIS FINALMAGDAL. (CRESWELLIAN)			? *cf. Magdalen.* (CAPSIAN INFLUENCE)
				MAGDALENIAN (CRESWELLIAN)		? *Mousterian*	MAG. MICRO-LITHIC (GRIMALDIAN)
72000	LGl_2		PINHOLE MOUST. / FINAL LEVALL.	SOLUTRIAN UPP. AURIGNACIAN		MOUSTERIAN	SOLUTR. GRAVETTIAN (GRIMALDIAN)
			PINHOLE MOUST. / FINAL LEVALL.	MID. AURIGNACIAN AURIGNACIAN		MOUSTERIAN	MID. AURIGNAC.
115000	LGl_1		MOUST. / LEVALL. V			MOUSTERIAN	
	LIgl	MICOQUIAN *Upper Acheulian*	MOUSTERIAN *Tayac.* / *Levall. IV* MIDDLE LEVALL.		ACHEULIAN	MOUSTERIAN "MOUSTERIOID"	
187000	PGl_2	MIDDLE ACHEULIAN	MIDDLE LEVALLOIS				
		MIDDLE ACHEULIAN				"MOUSTERIOID"	
230000	PGl_1		EARLY LEVALLOIS				
	PIgl	MIDDLE ACHEULIAN LOWER ACHEULIAN	? *Levallois technique appearing* ? CLACTONIAN II		*(Abbevillian present but not dated)*	CLACTONIAN	
435000	$ApGl_2$						
476000	$ApGl_1$						
	ApIgl	ABBEVILLIAN	*Clactonian I*				
550000	EGl_2	CROMERIAN					
		NORVICIAN					
590000	EGl_1	IPSVICIAN					
VILLAFRANCHIAN		? *Abbevillian on Sicilian in Morocco*	? *pre-Red Crag flakes*				

FIG. 207.—Relationship of the European palaeolithic cultures to the *Vollgliederung* and Milankovitch's time-scale. Tentative datings in *italics*. C. core; F. flake; B. blade industries. F. E. Zeuner, *1862* (3), p. 286, fig. 80.

P. Beck and other believers in six Alpine glaciations[275] (see p. 937) encounter obvious difficulties and bracket the three glaciations of the north-west with the Thun, Riss and Würm glaciations of Switzerland and the four glaciations of Poland with the Kander, Thun, Riss and Würm. They find no equivalent for earlier Alpine glaciations which took place in Pliocene time, the Kander during the Calabrian and the cold flora of Varennes, and the Deckenschotter glaciations of Beck's Glaziopliocene before the Plaisancian and Astian.[276] These constitute the "great interglacial" when the Pliocene

flora of the Rhône Gulf contained 11 North American, 11 Chinese-Japanese, 6 Canary and 28 Mediterranean species.[277]

Correlation would be simplified had the maximum been synchronous throughout Europe. Though the assertion that the first glaciation was the greatest[278] in the Alps, north-west Europe and in Hungary (and Tien-shan) is incorrect, it is uncertain to which subsequent glaciation we should award the honour. According to Penck,[279] it should be given to the Mindel in the eastern Alps and the valleys of the Inn, Salzach and Iller, but in the western Alps, e.g. in the Isar, Rhine and the valleys of Switzerland and the French and Italian Alps, to the Riss glaciation. The difference has been attributed to glacial erosion in the eastern Alps—this is highly improbable—or to a Mindel-Riss elevation of the western Alps.[280] Others place the maximum in both east and west at the same date but disagree in giving this as Mindel,[281] Riss[282] or Würm.[283] It would seem, however, that the difference in extent between the Mindel and Riss is small and that these two glaciations compete for the maximum position[284] as do the Elster and Saale glaciations in north Germany (see below). A similar discrepancy existed in the Caucasus[285]: in the west the third glaciation was biggest, in the centre and east the second.

Uncertainty also exists in north Europe. While German geologists have reached some measure of agreement (see p. 939), Russian glacialists disagree, some placing the maximum during the last, the majority putting it in the penultimate glaciation (see p. 955). In Poland the Cracovian or Mindel was the largest. The glaciations in Germany at any rate seem to become progessively smaller, though the first two, measured in distance from the Scandinavian centre, were roughly the same as the following table indicates[286]:

	%
Pomeranian phase	87·5
Weichsel (= Brandenburg phase)	92·5
Warthe	95·0
Saale	97·5–102·5
Elster	100

The Alps (e.g. Iller-Lech) on the *Vollgliederung* interpretation[287] show a similar reduction after Mindel 2 which is taken as 100.

	%
Würm 3	85·5
Würm 2	95·5
Würm 1	90
Riss 2	92·5–98·5
Riss 1	95–110
Mindel 2	100
Mindel 1	95–96
Günz 2	90
Günz 1	81

The molluscan and floral differences of the various interglacials,[288] which should serve as auxiliary aids, have as yet yielded few positive results (see p. 910).

Rhine terraces. The Rhine terraces, with their highly important fossiliferous localities (Basle, Achenheim, Mauer, Frankfurt, Wetterau, Mosbach, Coblenz, Obercassel, Tegelen) and their palaeolithic stations all situated near the river,[289] provide a valuable link between the Alpine outwash and the Scandinavian drifts of the lower Rhine. This connexion, which may ultimately be strengthened by equating the Alpine succession with the terraces in the Vosges and Moselle or by dovetailing the Carpathian and Caucasian terraces and schotter with the Scandinavian drifts[290] and loess sheets (Tatra

maximum glaciation = Cracovian glaciation), has often been attempted but so far not very successfully because it is difficult to correlate through the middle Rhine section. Mineral analyses, on lines already begun,[291] should prove helpful.

The oldest Rhine terrace, usually up to 20 m thick, consists of milky quartz pebbles and cherts with Devonian greywacke and sandstone and the dark brown or grey Kieseloolith derived from the Senonian Milioliden bed (H. Pohlig) or the Muschelkalk (G. Fliegel). Pebble-shapes and structures and field-relationships prove it to be fluviatile.

This *Kieseloolithschotter*, as E. Kayser[292] named it, which proves the antecedence of the middle Rhine with respect to the rising Rhine Slate Mountains, descends northwards from 590 m near Basle to 225–360 m in the Neuwied basin, 158 m at Waurichen and 125–145 m farther north.[293] The fall is partly original and partly due to faulting; thus there is a drop of 126 m along the northern edge of the Rhine Slate Mountains.[294] The schotter make a flat cone in the Netherlands, 6–12 m thick except in contemporaneous fault-troughs where its thickness is 70 m[295] or at Vlodrop even 371 m.[296] From its patches on the Rhine Slate Mountains it can be followed into North Limburg and the Moselle,[297] and extensively into the Meuse.[298]

Although the terrace, referable to an Urrhein, Urmoselle and Urmeuse,[299] has been assigned to the Günz glaciation,[300] to a "preglacial"[301] or interglacial[302] age, or to various ages which lessen as it is followed northwards into the Pliocene Sea,[303] it is probably upper Pliocene[304] and possibly in part Miocene,[305] as is proved on morphological grounds.[306] It marks the first drainage of central Europe in a northerly direction and is connected with the Dinotherian Sands of the Mainz basin,[307] which are upper Miocene (R. Lepsius, A. Steuer) or lower Pliocene (M. Schlosser), and as in the lower Rhine alternates with lower Pliocene clays containing a Mediterranean flora,[308] or overlies marine Pliocene.[309]

The Main Terrace[310] (Dut. *Hoofdterras*) is the Moséen or Campignien of Belgium,[311] and in the Rhine as well as in the Moselle, Lahn and other valleys occurs about the topographic shoulder—the lower Rhine has much higher terraces.[312] It consists in the Rhine gorge of local material with eruptive ingredients, badly weathered and increasingly fine textured as traced northwards. It falls from 180 m north of the Siebengebirge to 41 m at the Dutch frontier.[313] It is really a series of terraces, sometimes very broad, e.g. at Linz (7 km) at the embouchure from the Rhine gorge, and in the Netherlands[314] where its vast delta forms the Rhine-Meuse Diluvium or High Terrace Plain.[315] It has two horizons in the Meuse and lower Rhine,[316] separated by the Tiglian stage, and in the Neuwied basin,[317] and below Coblenz and in the Moselle[318] splits still further. The Mosbach Sands, with their fauna (*Elephas meridionalis*, *Mastodon arvernensis* and *Trogontherium cuvieri*), belong apparently to the Main Terrace.[319]

Kayser's Middle Rhine Terrace[320] (Dut. *middenterras*), subdivided by G. Steinmann[321] into High and Middle Terrace and much later by C. Mordziol[322] into the *Talhangterrasse* above and *Talwegterrasse* below, is well displayed near Basle, near Bonn and in the Moselle below Épinal; under Köln it is 18 m thick.[323] It is separated from the Main Terrace by a phase of downcutting which between Bonn and Köln was about 100 m[324] and represented almost one half of the duration of the whole Glacial period, so that the Rhine and Meuse and their tributaries have eroded deeply into the

Main Terrace, and the Middle Terrace, bordered by high banks, covers their broad floors.

The Lower Terrace (Dut. *Laagterras*: fig. 208), generally about 5 m above the present river (in the Netherlands it is under the alluvium) is double[325] or treble[326] in the Saar, Neckar and lower and upper Rhine, being either late-Pleistocene and Recent in age[327] or belonging to Würm 1, 2 and 3.[328] In this terrace-complex there exists an interstadial horizon with warmer plants.[329]

The one glaciation definitely established for the lower Rhine, the Saale—it pushed the *Paludina*, here called the Krefeld Beds,[330] into its stau-moraine at Hülserberg, Eyellscher Berg, etc.—is usually linked with the Lower Middle Terrace,[331] as it is in the Ruhr valley,[332] though it is often equated with the Main Terrace, since the land and freshwater molluscs of this terrace are relatively cold[333]; it encloses northern material[334] and big blocks, probably transported by drift-ice[335]; and it is associated with overflow valleys, due to ponding by Scandinavian ice,[336] and with boulder-clays and ice-pressure disturbances[337] between Krefeld and Nijmegen, on Dachsburg and Duisburg, and on the north-west slopes of Hülserberg. Its equivalents in the tributaries are contemporaneous with moraines in the Taunus, Odenwald and Vosges.[338]

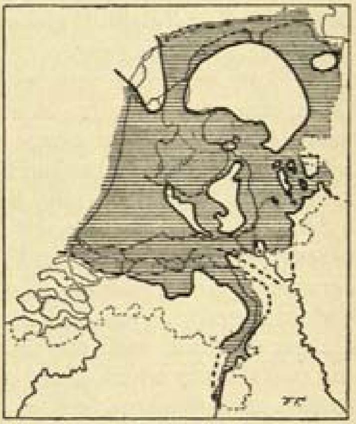

Fig. 208.—Distribution of the Lower Terrace in Holland. P. Tesch & F. J. Faber, *477*, p. 398, fig. 126.

The Tiglian beds[339] are interglacial. First found at Tegelen (Lat. *Tiglia*) in the Meuse, and later in the Rhine, they underlie considerable areas in the two valleys, extending southwards and south-westwards to beyond Brüggen and, without the flora, to west of Köln and between Kleve and Nijmegen—the horizon of Neede in Overyssel, with *Paludina* (*Vivipara*) *diluviana*, *Valvata naticina*, *Cervus elephas*, *Equus süssenbornensis*, *Elephas antiquus*, *Diceros merckii* and *Vitis vinifera*, *Nuphar lutea*, *Alnus*, *Pinus* and *Acer*, is apparently younger than the Tiglian since it contains only 19% of exotic plants compared with the 40% of Tiglian[340] (cf. p. 910). The Tiglian beds consist of peats, fine green or grey sands and clays, with a high percentage of calcium carbonate and were deposited in a lake traversed by the Rhine Their land and freshwater forms[341] include *Trapa natans*, *Vitis vinifera*, *Cornus mas*, *Nuphar lutea*, *Abies pectinata*, *Paludina diluviana*, *Valvata naticina*, *Bythinia tentaculata* and *Unios*. *Viviparus glacialis* is the most conspicuous mollusc. Their plants,[342] which contain 66 genera, generally denoting drier and slightly more southerly conditions, include exotic species from east Asia—the non-European "Tertiary" genera are *Actinidia*, *Decodon*, *Dulichium*, *Eucommia*, *Euryale*, *Magnolia*, *Menispermum*, *Phellodendron* and *Pterocarya*. The mammals[343] also bear the impress of a warmer climate, for they comprise *Equus stenonis*, *Rhinoceros etruscus*, several species of Cervidae including *Cervus sedgwicki*, *Trogontherium cuvieri*, *Hippopotamus*, *Elephas meridionalis*, *Macacus* cf. *florentinus* Cocchi and some small vertebrates including *Microtus intermedius* of the Cromer Forest Bed. The fauna, however, shows none of the palaeontological contrasts of the

latter (see p. 995), the plants and animals clearly belonging to one age and one climate. The bones, unlike those of the Forest Bed, have their fine superficial sculpture intact.

The age of the Tiglian is controversial.[344] It has been given as Pliocene[345] or earlier than the Cromerian[346] (= Norwich Crag and Chillesford Clay or Butley-Weybourne Crag interval) and equivalent to the beds of Frankfurt-am-Main[347]: the flora denotes a climate 4–5°C warmer than now, has Asian species and reveals an uninterrupted floral succession from the upper Pliocene. Nevertheless, it probably belongs to the earliest interglacial[348] or Günz-Mindel[349] since it overlies in the region of Dordrecht[350] marine sediments with a cold fauna containing *Yoldia arctica*, *Astarte borealis* and *Cardium groenlandicum* and near Venlo a clay with cryoturbate structure,[351] and its mineral content (e.g. garnet, epidote, hornblende) proves that the northern ice ("Elbe" or "Baltic" glaciation, see p. 941) lay within the Rhine-Meuse delta area. It has, however, been put in the interstadial of the first glaciation[352] or made as late as the Mindel-Riss interglacial.[353] The early Pleistocene flora in the Schwanheim-Kelsterbach Terrace in the Mainz basin,[354] with 24% of exotic species, belongs to the same interglacial (see p. 693). A similar fauna and flora has been found in south-west Germany,[355] in Dalmatia[356] and in Italy, Belgium, France, Austria and Hungary.[357]

Although the Rhine terraces are coeval with the glaciations (H. Quiring[358] dissents and R. Grahmann[359] equates them with interglacials, viz. Main Terrace = Günz-Mindel, Upper Middle Terrace = Mindel-Riss, Lower Middle Terrace = Riss-Würm and Lower Terrace = Würm 1–2), the manner of their equation with the Dutch and German drifts has divided geologists into two schools which differ upon the number of times the Scandinavian ice pressed into the area (see p. 941) and the age of the terrace it disturbed. The older view,[360] recently revived, equates the Main and Middle terraces with the Saale and Weichsel glaciations respectively, the Lower Terrace with the alluvium, and the loess with the last glaciation. The Main Terrace alone, it contends, is outside the end-moraine of the Saale glaciation, the Middle and Lower Terraces occurring within it, while the Main Terrace east of the Rhine overlies boulder-clay and has northern erratics embedded in it beyond the moraines. The state of weathering of the various drifts and terraces is in harmony.

The other school displaces the correlation by one glaciation and brackets each terrace (Main, Middle, Lower) with a glaciation[361] (Elster, Saale, Weichsel)—the upper plateau terrace of the Neuwied basin (see above) is equated with the Günz. It emphasises the relationships to the Eem zone and the *Paludina* beds; the Main Terrace's association with boulder-clays and ice-disturbances (see above); and, especially, the glacial age of the Lower Terrace which contains remains of woolly rhinoceros[362] and, like the last drift (see p. 521), excludes the loess which was contemporaneous with the deposits and the flooding of the terrace.[363] The *Hoogterras* is equated with the Riss.[364]

Correlation of the Alpine and Scandinavian glaciations by these terraces is extremely attractive: the Alpine drifts and outwash terraces grade into the Rhine terraces about Basle where the Deckenschotter is 156 m, the Hochterrasse 70 m and the Niederterrasse 36 m above the present Rhine[365]; the terraces of the lower Rhine fall within the bounds of the Scandinavian glaciation; and the terraces of the upper and lower Rhine pass through the

Rhine gorge. Unfortunately, each link is somewhat weak; and attempts to follow the terraces through the Rhine gorge[366] have met with indifferent success. The terraces, including the Main Terrace,[367] are poorly developed over this stretch, except in the youthful tectonic Neuwied basin where several plateau, valley slope and valley floor terraces are distinguished; intercrossing and splitting have introduced confusion of levels (see p. 1267); and each terrace is frequently double like the glaciation[368] (see p. 919). The middle Rhine stretch has been uplifted: F. Klute and W. Will[369] have concluded as follows: uplift was strong and rapid after the Main Terrace (Günz), was weaker and slower between High (Mindel) and Talwegterrace (Riss) and small but rapid after the Talwegterrace and Lower Terrace (Würm). Faulting and epeirogenetic movements which were probably not simultaneous everywhere or in the same sense or of equal intensity have, for example, buried the Deckenschotter at considerable depths in the Rhine rift valley. Near Basle, the Hochterrasse is above the Niederterrasse (see above), south of Mulhouse the position of the terraces is reversed. Near Karlsruhe the bottom of the glacial schotter is below sea-level, at Mannheim at −55 m O.D. and at Heppenheim at −250 m.[370] According to Mordziol,[371] Steinmann's Middle Terrace is the continuation of the Sockelschotter (Riss) above Basle and his Talwegterrace, of Riss-Saale age and the only Rhine Terrace in immediate relation to the moraines of the two regions, is the only stratigraphical link. Firm conclusions will only be arrived at when the terraces throughout their course have been studied petrologically like those in Holland,[372] and when the parts played by glacio-eustasy (see p. 1354)—this has led to the correlation of the terraces with interglacial periods (see p. 1044)—and by tectonic movements (see p. 1265) have been properly assessed.

The loess horizons,[373] two in number in the upper Rhine, e.g. about Wiesbaden and Wetterau, and in the Eifel and lower Rhine have, however, been especially valuable. The older loess is younger than Steinmann's High Terrace or the youngest Middle Terrace[374] and the newer loess, as noticed already, is the same age as the Lower Terrace (loess, said to occur on the Lower Terrace in the upper Rhine,[375] is not true loess[376]).

Since the two loess horizons belong to the Riss and Würm (see p. 1027), it follows that the Lower Middle Terrace in the Rhine gorge and lower Rhine and the Middle Terrace in the Mainz basin and upper Rhine are roughly equivalent to the Riss, and the Lower Terrace to the Würm[377]—L. v. Werveke[378] alone dissents. The Main Terrace is probably equivalent to the Swiss Deckenschotter,[379] the Elster glaciation of north Germany, and the one glaciation definitely proved for the lower Rhine. While the Tiglian is correlated with Günz-Mindel, the Krefeld Beds are referred to the Mindel-Riss, and the Moers and München-Gladbach beds to the Riss-Würm.[380]

The previous considerations may justify the following tentative but reasonable correlations:

Alpine Glaciation	*Upper Rhine*	*Lower Rhine*	*North German Glaciation*
Würm	Lower Terrace	Lower Terrace	Weichsel
Riss	Middle Terrace	Lower Middle Terrace	Saale (and Warthe)
Mindel	Main Terrace	Main Terrace	Elster
Günz	Upper Terrace (?)	Older Terraces	Elbe (?)

This correlation is supported by the testimony of the tributaries,[381] e.g. the Lahn and Main and those draining the southern slopes of the west Taunus, as well as by the parallel history of the Moselle[382] and Meuse,[383] whose terraces below Liège spread more and more to the north and finally cover the Bas-Plateau of Campine and southern Dutch Limburg (fig. 209). In a dissident view the various members of the Main Terrace of the Meuse—deposits containing *Vivipara diluviana* lie underneath this terrace—have been equated with the Günz, Mindel and Riss 1, the Middle Terrace with Riss 2, and the Lower Terrace with Würm.[384] In the Schelde, which was not fed by melt-water from glaciers, terraces corresponding to the Mindel and Riss glaciations are unknown.[385]

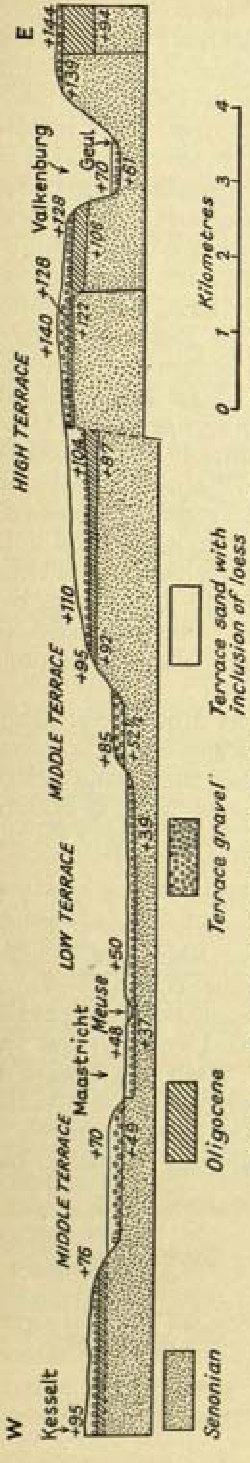

FIG. 209.—West-east profile through the Meuse terraces of south Limburg. Vertical scale is exaggerated 10 times. F. J. Faber, 477, p. 397, fig. 125.

The state of weathering and varied topography of the drifts, and their relation to the two loess horizons agree in equating the Mindel and Riss drifts with the Elster and Saale glaciations. The Weichsel and Würm have unanimously been treated together, the latter being linked with the Fläming or Brandenburg phase. This, however, has been equated with Würm 1 and the Pomeranian phase with Würm 2.[386] The Warthe may be Riss 2.

On the *Vollgliederung* hypothesis,[387] the lower and upper Main Terrace are equated with Mindel 1 and Mindel 2, the Middle Terrace in general with the Riss, and the two members of the Lower Terrace with Würm 1 and 2.

H. Gams[388] has correlated the various fossiliferous horizons of continental Europe as set out in the table opposite.

Palaeolithic cultures. The relation of the drifts in north Germany to the palaeolithic cultures[389] is by no means so helpful as might be expected; for the rigorous climate of this more easterly area was less conducive to human habitation. No Abbevillean or Acheulian (see below) has been found over the glaciated area of central or eastern Europe. But apart from this and from the implements which are probably eolithic or Campignian in facies,[390] such as the alleged Mousterian industry of Schaalsee near Lübeck[391] and the doubtful artefacts claimed as palaeolithic,[392] there is ambiguity through the clash of opinion about the cultural age of particular implements. More than elsewhere, classification, whether by allocation to types or by technique, is largely a matter of personal judgment.

While the palaeolithic sites in Germany, e.g. the caves[393] and Mauer[394] (generally placed in the first interglacial), are outside the limits of the drifts, a number of stations occur within the influence of the Elster and Saale glaciations[395]: they include south Hannover,[396] Thiede and Westeregeln (the northernmost definitely established palaeolithic sites in Germany), Markkleeberg, Taubach, Weimar and Ehringsdorf, all in the Ilm valley of Thuringia,[397] and Wangen, Hochstedt and Wettin in central Germany.[398] These were formerly regarded as Acheulian (I and II) but are referable to early Levalloisian and associated with the oncoming of the Saale glaciation (Levallois

Pliocene and Pleistocene Stratigraphy of North, Central and Southern Europe

Primigenius	Würm 2	Weichsel 2
	Aurignacian oscillation	Rixdorf horizon
	Würm 1	Weichsel 1
	Older Schieferkohlen	Eemian
	Riss 2	Fläming-Warthe Readvance
Antiquus	Riss 1	Saale glaciation
	Great Interglacial	Great Interglacial
		Cannstatt
	Mindel 2	Elster 2
	Younger peat of Leffe	Mosbach, Mauer, etc.
		Cromer Forest Bed
		Weybourne Crag
Meridionalis	Mindel 1	Elster 1
	Val d'Arno	Schwanheim, Tegelen, etc.
	Villafranca	(Tiglian)
	Laaerberg Terrace	
	Günz 2	Norwich Crag
	Older peat of Leffe	Reuver sands, etc.
	Günz 1	(Pre-Tiglian)
	Calabrian	Reuver clays, etc.
Mastodont	Astian	Frankfurt Klärbecken
	Pliacentian	Kroščienko
	Post-Pannon	Sundgau Schotter and
	Congerian Beds	Danube glaciation

flakes are embedded in its outwash[399]). At Markkleeberg, near Leipzig, lower Levallois implements[400] (also referred to Chellean or Acheulian[401]), with mammoth and woolly rhinoceros, belong to the advance phase of the Saale glaciation[402]: its late Clactonian implements are the oldest implements in Germany. Of Elster-Saale date are the Middle Clactonian of Gronau and Döhren, the Clactonian of the Wangen Terrace in the Unstrutt valley, and the implements of the Main Terrace of the Saale and the Middle Terrace of the other central German rivers and of Hundisberg.[403]

The implements of the interglacial travertines of Taubach, Weimar and Ehringsdorf (with *Elephas antiquus* and *Diceros merckii*), which are variously claimed[404] as Chellean, "warm" Mousterian or "Ilmian", are late Acheulian and the equivalent of the Saale-Weichsel interglacial or Alpine Riss-Würm.[405] The Micoquean of the Rabutz Clay also belongs to this interglacial.[406] The implements of Hundisberg, near Magdeburg, have been regarded as Acheulian and interglacial[407] or as Mousterian (Levalloisian) and Riss glacial in age.[408]

While the lower Palaeolithic in both Germany and Poland is situated outside the limits of the last glaciation[409]—Acheulian hand axes and flakes occur chiefly between the Elbe and Weser outside the Warthe and Weichsel moraines but inside those of the Saale and Elster glaciations[410]—Mousterian implements, with mammoth, woolly rhinoceros and reindeer, are found in the drift succession of the Rhine-Herne Canal,[411] and early Mousterian skeletal remains in the Kieselgur of the Lüneburger Heide.[412] Other palaeoliths have been found at Grünewald near Berlin.[413]

Mousterian implements in the lower rodent layer, assigned either to the Riss or Würm (see p. 1037), are followed by Aurignacian with the steppe fauna of *Felis leo*, *Equus caballus* and *Cervus megaceros*, which is widespread in the younger loess, e.g. Leine, Saale, Saxony, Thuringia and Upper Silesia. Traces of upper palaeolithic man have been discovered near Berlin and Brörup within the Baltic moraines,[414] occasionally in interglacial beds or in later drifts derived from them. In the area of Lake Pulawy, Poland, Solutrean implements, probably obtaining their material from nearby Chalk outcrops, were abstracted from clays of a glacier-lake impounded by the last ice-sheet.[415] The Aurignacian belongs to the last interglacial, as A. Jessen, V. Milthers, A. Penck and F. Wiegers maintain, or to the interstadial following the Mousterian of the Brandenburg advance.[416] The Magdalenian, on the strength of the stations near Brandenburg and Hamburg (types related to the Creswellian or Swidérian[417]), is regarded as synchronous with retreat stages[418] of the Weichsel or the Gotiglacial: it has been found as far north as Sylt.[419]

Of the human remains Heidelberg man probably belongs to the first interglacial, Steinheim to the second, and Ehringsdorf to the third. Neanderthal man belongs to the last glaciation.

In Schleswig-Holstein, G. Schwantes[420] recognised the following six stages after the retreat of the ice: Schlutup stage near Lübeck in lateglacial beds with reindeer antlers; Schaalsee stage with survivals of palaeolithic forms; Ahrensburg stage (see p. 880); Duvensee stage (= Lyngby culture); Boberg stage with Tardenoisian microliths; and Oldesloe stage (= Gudenaa stage of Denmark).

The two glaciations often recognised by Polish geologists are correlated with the Riss and Würm,[421] though the three glaciations also recognised (see p. 954) are equated,[422] on the basis of their morphology, loess and prehistory, with the Mindel, Riss and Würm (Saks, 1947) or with the Riss and Würm 1 and 2 (L. Sawicki). Kurowski[423] has mapped the palaeolithic sites. In Russia, the outermost drift, of obscure age, has been related to the palaeoliths[424] and equated with the Saale glaciation[425] or with the Mindel,[426] Riss[427] or Würm.[428]

The palaeolithic occurrences in the Low Countries[429] do not throw any light upon the question of correlation, though both lower and upper palaeoliths have been found without and within the limits of the maximum glaciation in Holland.[430]

Believers in Milankovitch's curve and its glacial and interglacial equivalents (see pp. 919, 1544) correlate Elster with Mindel 2, Saale with Riss 2, Warthe with Würm 1, and Weichsel with Würm 2.[431] Others bracket Warthe with Würm 2 and Brandenburg moraines with Würm 3.[432]

The river-terraces of central Europe, e.g. Saxony, contain few palaeoliths but fortunately are associated with warm travertines and with cold loess and solifluxion deposits.

(*b*) *British Isles and Continental Europe*

Correlation of the British with the continental drifts of Europe is even more difficult than that just considered. It is uncertain which British glaciation was maximum though the honour should perhaps be awarded to the Great Chalky Boulder-clay and its equivalents. The identity of the "great interglacial" is also in dispute: it may have been the "Hoxne interglacial"[433] which was characterised by a marked climatic amelioration and by aggradation of the valleys. The Eemian has been correlated with the Swanscombe Terrace of the Thames,[434] with the *Corbicula fluminalis* gravels of Holderness and March, with Kirmington,[435] and with the Cromerian[436]—O. Torell[437] early equated the *Cyprina* Clays with the *Leda myalis* Bed. The Newer Red and Weybourne Crags are usually equated with the Günz (or its two phases).

The three post-Cromerian glaciations usually recognised are generally assigned to the last three Alpine glaciations,[438] though the Great Chalky Boulder-clay has been equated with the Mindel[439] and Würm[440] (and the Baltic Moraines[441]), and the Newer Drift, correlated with the last Danish and German glaciation,[442] has been bracketed with the Saale or Warthe glaciation[443]—the Cromer Ridge is joined up with the East Jutland moraine and the Warthe glaciation.[444] The three British glaciations have, therefore, been equated with the Günz, Mindel and Riss[445] or with the Riss (two glaciations) and Würm.[446] The Cae Gwyn and other Aurignacian caves of North Wales are referred to the Laufen oscillation[447] which was followed by the Magdalenian glaciation. The mammoths of Scotland (see p. 809) have been placed in the Riss-Würm,[448] and the District Glaciation (see p. 1207) has been correlated with the Ponders End beds and their equivalents[449] and with the Baltic Moraines[450] and the Solutrean[451] (and even with the Riss glaciation[452]). H. Breuil[453] places the 100-ft terrace of the Thames in the pre-Mindel age, the 50-ft terrace in the Mindel-Riss interglacial, and the coombe-rocks that overlie the terraces in the Mindel and Riss glaciations. The Ponders End stage has been equated with Würm 1[454] and not as generally supposed with the Magdalenian or Würm 2.

The following correlation has been made[455]: later Crags = Günz; North Sea Drift = Mindel; Great Chalky Boulder-clay = Riss; Upper Chalky Drift = Würm 1; Hunstanton Boulder-clay = Würm 2. Much may be said in favour of equating the Cromer Forest Bed with Mosbach and Mauer (though the microtine fauna suggests that the Forest Bed is somewhat younger[456]). The Corton Sands are probably the equivalent of the "Marine high terrace" of the Netherlands[457] and the Holstein Sea—Kirmington has also been placed on this horizon[458]—and the Little Eastern glaciation of the Warthe. The mammalian faunas and drifts may be correlated as follows[459]:

European Correlations

England (see pp. 1016–1017)	*Germany* (see p. 953)	*Alps*
York Line	Weichsel	Würm
Clacton: Crayford: March Great Chalky Boulder-clay	*Ehringsdorf: Rixdorf: Eemian Sea* Saale	*Riss-Würm* Riss
Ilford: Corton North Sea Drift	*Cannstatt: Münster: Holstein Sea* Elster	*Mindel-Riss* Mindel
Cromer Forest Bed Late Crags	*Mauer: Mosbach* Elbe?	*Günz-Mindel* Günz

(c) *Transatlantic Correlations*

It has been asserted, on untenable grounds,[460] that the glaciations about the North Atlantic were not synchronous: the North American ice and its attendant anticyclones synchronised with warm south-west winds over Europe and a vast cyclone over the North Atlantic, and the glacial epochs of North America alternated with interglacial epochs in Europe and vice versa (see p. 1539). Alternatively, glaciation in regions of continental and oceanic climate alternated[461] and the ice in the northern hemisphere was no bigger than in the Arctic to-day: a shifting polar cap explains extensive glaciation (see pp. 625, 1538). Again, the four Alpine glaciations have been made equivalent to the four phases of the Wisconsin.[462]

Nevertheless, the glacial successions on opposite sides of the North Atlantic were almost certainly in general coeval. They were in the same climatic zone; their ice-extents and glacial curves were similar; their glacial snow-lines[463] and fossil isoflors[464] were similarly depressed; their several drifts were weathered to a like degree[465]; their ice-sheets disappeared contemporaneously—Post Bühl in Switzerland was 20,000 years,[466] postglacial time in Sweden 13,000–14,000 years,[467] the Niagara and Toronto regions were freed 20,000–25,000 years ago,[468] post-Wisconsin was 25,000–30,000 years,[469] and Lake Agassiz's final stage was 10,000 years ago.[470] Their late-Pleistocene climatic changes were generally parallel[471] (the belts of retardation are of like width and are similarly situated within the glaciated areas[472]), as were those of the Alleröd oscillation (see p. 1431), of the Climatic Optimum (see p. 1482) and the climatic stress of the 14th century A.D.[473] (see p. 1502). The epi-glacial upwarping of the lands was comparable[474]—the rate in both regions has decreased during the last 5000 years to about half its previous value—as is the present-day glacier retreat[475] (see p. 146).

Precise correlation, however, presents its difficulties. The mammalian faunas show certain differences (see ch. XXXIV); North America has no palaeolithic cultures (cf. p. 867) or deposits resembling the Cromerian; the number of the glaciations is discordant—hence the Illinoian and Iowan have been bracketed with Riss 1 and 2,[476] the five American glaciations are classified with the classic Alpine four, plus either the early Donau glaciation[477] or the Néowürm,[478] the Alpine four are bracketed with the Illinoian, Iowan, Early and Late Wisconsin, the Jerseyan and Kansan having no European equivalents,[479] and the three North German glaciations are raised to the standard four by the insertion of a "Middle Drift" or in other ways (see p. 941). Lastly, it is uncertain to which of the American interglacial epochs the title "great" should be awarded (see below).

When the glacial marine record in the North Atlantic Ocean (see p. 921), which presumably is continuous, has been discovered by cores taken along the meridians from the Arctic Ocean into the tropics a new approach may be opened to the correlation we seek. Until this has been done or some other means of correlation has been discovered, the four North American glaciations may speculatively but reasonably be equated as follows[480]—the position of the Warthe is uncertain but may have its counterpart in a second stage of the Illinoian (Flint, 1953).

Among the reasons which may be assigned for this correlation are the following: the several drifts have the same ratio to the total glaciated area in the respective regions[481]; the Nebraskan drift, like the Günz and Elbe

Alps	*North Germany* (see p. 953)	*British Isles* (see pp. 1016, 1017)	*North America*
Würm 3	Pomeranian	North British	Mankato Cary
Würm 2	Frankfurt	York Line	Tazewell
Würm 1	Brandenburg	Hunstanton Boulder-clay	Iowan
Riss-Würm	*Ehringsdorf*: *Eemian*	*Taplow: March-Nar*	*Sangamon*
Riss 2	Warthe	Upper Chalky Drift (?)	Illinoian 2
Riss 1	Saale	Great Chalky Boulder-clay	Illinoian 1
Mindel-Riss	*Paludina*: *Holstein*	*Corton Sands*	*Yarmouth*
Mindel	Elster	North Sea Drift	Kansan
Günz-Mindel	*Mauer: Mosbach*	*Cromerian* (in part)	*Aftonian*
Günz	Elbe?	Later Crags	Nebraskan

glaciation of Europe, was less extensive than the later drifts[482]; the maximum, in general, was during the second glaciation[483]; the main loess horizon occurs between the third and fourth drifts; the "great interglacial" in North America was probably the Yarmouth[484]; the Iowan may be the equivalent of the Warthe[485] which shows much resemblance in the uncertainty of its exact position relative to the preceding and following glaciations though the Warthe may be, as in Germany, a second stage of the penultimate (Illinoian or Saale) glaciation[486]; the topography of the Würm, Weichsel, Newer Drift and Wisconsin is fresh and youthful[487]—the equation of the Wisconsin with the Ra or Gotiglacial moraines[488] or with the Riss and Würm[489] has nothing to commend it; and the great recessional moraines in North America and North Germany are strikingly similar in their arrangement and distribution.[490]

In Europe, it is held that the three older glaciations were double and the last glaciation double or triple: this is suggested by the evidence of the Alps (see p. 937), of the periglacial terraces of central Germany (see p. 919), of the Somme terraces, and of evidence from other areas (see p. 919). The sudden influx of arctic shells which occurred twice in the East Anglian Crags (Newer Red Crag and Weybourne Crag: see p. 599) also suggests that the first glaciation (Günz?) was double. Except in the Wisconsin, North America has little or no evidence of this *Vollgliederung*, though the loess horizons may indicate advances hitherto unrecognised.[491]

A correlation between North and South America is difficult: the faunas show considerable differences, and in both north and south survived until a late stage[492] (see p. 865).

(*d*) *World Correlations*

A correlation table for the world is at present somewhat speculative: it is claimed,[493] for example, that climatic alternations diminished eastwards in Eurasia, and that Europe had four glaciations, European Russia three and Asia two. Nevertheless, occasional attempts to link Africa and Asia with Europe and America have been made[494] on the basis of fluctuations in the power-volume of rivers and of orogenic and tectonic movements which give three major cycles. Palaeolithic cultures are a very uncertain basis (see ch. XXXV), if only because of hybridisation and faulty synchronisation of the cultures. The mammalia appeared and disappeared at different times. Thus while *Elephas namadicus* was at the same stage of development as

E. antiquus and *Bos namadicus* was a close ally of *Bos primigenius*, *Stegodon* died out in China in lower Pleistocene, in India in middle Pleistocene, and in Java at the close of the Pleistocene.[495] The sequence in north and east Africa is only provisionally outlined, and many difficulties attend the making of correlations even in small regions.

Mean sea-levels, if they could be exactly determined for each stage, should provide a useful check, as should the climatic rhythm of river aggradation and erosion, as developed in both glacial and pluvial regions.

The following table for Asia is based upon the correlations made by several authors[496]:

PLEISTOCENE SUCCESSIONS IN ASIA

Epoch	*North India*	*Java*	*Yunnan*	*Burma*	*South China*	*North China*
Upper Pleistocene	Potwar	Ngandong fauna (*H. soloensis*)	Heiching-Lungstun Shelter	T4 T3 T2	?	Malan loess Upper cave deposits
Middle Pleistocene	Narbada and Boulder Conglomerate	Trinil fauna (*P. erectus*)	Hoshangtun Cave	T1 Mogok Caves	Kwangsi Caves Yen-Ching Kou Pits	Choukoutien Upper Sanmenian
Lower Pleistocene (Villafranchian)	Pinjor	Djetis (*H. modjokertensis*)	Mai-kai	Upper Irrawaddian	?	Lower Sanmenian (Nihowan-Taiku) Beds Basal Conglomerate
Astian	Tatrot	Kali Glagah Tji Djulang				

While the "Boulder Conglomerate" of India is Pleistocene—it contains *Bos*, *Equus* and *Elephas namadicus* and glacial debris—and the Pinjor is by some[497] referred to the Pliocene, this horizon seems to belong to the Villafranchian age of Europe, for it contains, besides persistent forms, *Equus*, camel, early mammoth, *Leptobos* and other advanced mammalian types. Even the Tatrot which has some of these forms is assigned to the Pleistocene,[498] though it is better regarded as transitional.[499]

The Plio-Pleistocene mammalian fauna of Java (Tji Djulang) is closely related to the Upper Siwalik fauna of India (Tatrot), the Siva-Malayan fauna of von Koenigswald,[500] which migrated from India—the fauna includes *Elephas planifrons* and *Hippopotamus*. The Kali Glagah fauna, which is less well defined, contains *Mastodon bumiajuensis*, *Stegodon*, *Elephas* cf. *planifrons*, *Sus stremmi*, *Mantiacus*, *Cervus stehlini*, *Bos* sp. and *Hippopotamus simplex*.[501] The Djetis fauna includes *Felis*, *Epimachairodus*, *Lutra*, *Megacyon*, *Ursus*, *Hyaena*, *Hippopotamus koenigswaldi*, *Cervus problematicus*, *C. zwaani*, *Antelope modjokertensis*, *A. saatensis*, *Bos*, *Rhinoceros sondaicus*, *R. kendengindicus*, *Tapirus*, *Nestoritherium*, *Stegodon*, *Elephas* sp., with monkeys, gibbons, orang and man[502] (*Meganthropus* and *Pithecanthropus*). The Mogok Cave fauna (e.g. *Stegodon orientalis*, *Elephas namadicus*) of central Asia resembles closely the cave-fauna of south-west China and is the correlative of the Narbada

fauna of India and the Trinil fauna of Java—this is the Sino-Malayan fauna of von Koenigswald. The Trinil fauna differs from the preceding fauna in that *Epimachairodus*, *Nestoritherium*, *Leptobos* and other Tertiary types have disappeared. Guide fossils are *Cervus* (*Axis*) *lydekkeri* and *Duboisia kroesenii*. Additional are *Stegodon*, *Elephas* cf. *namadicus* and *Pithecanthropus erectus*. In the Ngandong fauna the antelopes have disappeared and *Hippopotamus*, *Stegodon* and *Elephas* are highly specialised. Characteristic are *Cervus palaeojavanicus*, *Sus terhaari* and *Homo soloensis*. The middle Pleistocene on the mainland is commonly preserved in caves, e.g. Mogok, Hoshangtun, Trinil, Kwangsi, Szechwan, Chou-k'ou-tien.

Correlation of South Africa with the rest of the world is very difficult since the majority of the fossil mammalia are not closely related to those of Eurasia and are even less related to those of America. In East Africa, where many animals which became extinct in Europe survived into the middle Pleistocene, e.g. *Deinotherium*, *Chalicotherium* and *Hipparion*, the correlation with Europe may be made as in the table facing p. 1128.

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Chapter XL

PERIGLACIAL REGIONS

The ice-sheets and other large ice-masses of the Glacial period had fringes of unknown but doubtless considerable width where periglacial processes, already described (Part III), were actively at work on both land and sea.

1. On Land

(a) *Frost and Solifluxion*

General. The periglacial zone of the Pleistocene, whose importance has been realised only during this century, was characterised by severe cold and by snow on those parts (H. Lecoq's *terrain névéen*[1]) which, though high, were too low to nourish glaciers. These conditions, which the nearness of the ice and its overlying anticyclone induced, are proved by the flora and fauna and by evidence of widespread solifluxion and by kindred phenomena.

Analogy with the present Arctic is untrustworthy; for the periglacial zone in Europe and North America was physically different; its topography was more level and its ice terminated mostly on land instead of in the sea. It also differed climatically, as in its heat and light and sunlight periods.[2] It had no long winter night; its temperature oscillated more widely; and (assuming neither continental displacement nor polar movement), the sun's rays, important in their physiographical influences upon the vegetation, were incident at a higher angle. It differed too from the Alpine climate which has violent temperature changes, heavy rains, hailstorms and snow, rarefied air, more intense light, and greater warming of the ground during the day. The climate, therefore, was neither arctic nor alpine but glacial (see p. 1075).

Despite statements to the contrary,[3] the ice-sheets seem to have had a broad belt of frozen ground about them,[4] especially in the more continental regions, as may be implied for the last glaciation by the even surfaces of the older drifts (cf. p. 1150). Thus *Seerinnen* were preserved in the North German *Urstromtäler*[5]; frost cracks, pseudomorphs after ice-wedges filled with loess or local material which later slumped in, occurred in drifts and other rocks in France,[6] Denmark,[7] Holland and Germany[8] (e.g. Westphalia, Aschaffenburg, Weimar, Dresden, Gera, Göttingen, Ehringsdorf, Silesia), Hungary,[9] Bohemia and Moravia,[10] Russia,[11] the British Isles[12] (on the Cleveland Hills, at Lincoln, in Co. Durham, at Cambridge (Traveller's Rest Pit), near Whittlesey (Fens) and near Londonderry), and in North America[13] —they are up to 75 m long and 6 m deep; solifluxion phenomena (see below), including contorted gravels, were widespread,[14] as in south-east England and north France; fossil *Karren* were formed[15]; boulders were transported to considerable distances[16]; valleys were made asymmetrical, e.g. in various parts of Germany[17]; peats and marshy vegetation grew on very pervious sands in Holland[18]; "dry valleys" were excavated in permeable rocks (see below); and reduced percolation due to the frozen ground caused glacial cave sediments to be relatively thin[19]—the rate of accumulation in central European caves may have averaged 2 cm per century. Frost-heaving occurred in

Holland[20] and even near Bordeaux,[21] palsen[22] in Poland and Washington, and stone-nets or rings,[23] e.g. in Holland, Denmark, Schleswig-Holstein, Hungary, the Vienna basin, France and near Aberdeen.

The depth of the Pleistocene permafrost is unknown but in north Germany[24] may have been 3–4 m, i.e. the depth of the disturbed zone below the solifluxion layer—frost wedges give only the minimum depth. Both depth and extent probably changed considerably as the permafrost developed at each glaciation.[25] The thaw layer, determined by the depth of the solifluxion features, may have been 2–2·5 m[26] in the lower Rhine region and up to 3 m in Holland[27]; the thaw-lines, which ran east–west in the south of England and north-east–south-west in France, conform, like the treeline in these parts, to the low pressure oceanic "bay" coming into the Low Countries from north-west France.[28] The depth decreased into the cold area of central Europe but increased again into the Hungarian Plain which had a continental summer temperature.

Solifluxion, like all other periglacial effects, was displaced equatorwards; J. Büdel estimated the displacement between the meridians of 0° and 15° E. at 22–24° of latitude (see fig. 220, p. 1137), though the zone was then qualitatively different from that of to-day because of its lower latitude. Slides of thawed slush and soil, with involutions, garlands and *Taschenboden*,[29] were first found fossil in England where S. V. Wood[30] appreciated their true significance (see below). They were afterwards noticed in northern and southern France[31] (as far south as Bordeaux and the Mediterranean littoral), the Low Countries,[32] Germany[33] (including the Rabutz *Beckenton* and as far south as Swabia), and elsewhere in Europe[34]: in north France, they contributed much of the coarser material to the river-terraces.[35] Their role was considerable in the Gotiglacial tundras of south Sweden, and may have been responsible in central Europe for the present physical forms which are an inheritance from Pleistocene times[36] (pl. XXVIA, facing p. 913).

Stone-rivers existed on the Polish Mittelgebirge, the Lublin plateau, and the Wolhynia-Podolian Ridge.[37] Even fossil polygonal markings from these times, scarcely to be expected and sometimes denied,[38] are occasionally indicated (see above).

The Ice Age in North America favoured the formation of screes[39] and of creep,[40] gave rise to extensive landslides by frost-heaving,[41] and occasionally produced stone-stripes,[42] as on the Columbian Plateau. It also widened the valleys, as in the Appalachian Mountains of Pennsylvania and the St. Francois Mountains of Missouri.[43] In South America it contributed to the making of the Patagonian Pebble Beds[44] (*los rodados patagonicos*) which cover the high table-mountains and spread valleywards to the west coast.

Much of Europe was in the grip of the great frost. It shattered the rocks into blockfields in many localities (see below) and into screes as far south as Gibraltar[45] ("Older" and "Newer Limestone Agglomerates"), Malta[46] and Cyprus[47]—on the flanks of the Juras they grade into Pleistocene terraces; it lowered the *Schuttregion*[48] (by depressing the *Hochgebirgsregion* and the vegetation cover), thereby overloading the rivers (see p. 1026); it greatly accelerated erosive processes, e.g. of stream-action and solifluxion, even perhaps to a paroxysmic scale,[49] and by facilitating solifluxion produced the asymmetrical valleys of Germany[50] as it does in Siberia to-day.[51] It burst the surfaces of erratics on moraines,[52] developed terminal curvature and creep[53] and formed rock-cliffs,[54] like those of present Spitsbergen[55]; it

weathered the *Quadersandstein*[56] of Saxony and Bohemia (cf. p. 530) and the *Buntsandstein*[57] of the Vosges and Black Forest and by drying up springs interrupted the growth of tufa.[58]

In porous rocks, it produced valleys either quite dry or disproportionately big. These owe their existence possibly to cloudbursts,[59] but mainly to surface-streams when the ground was frozen,[60] as described from present-day Canada, Novaya Zemlya, Spitsbergen and Greenland.[61] They occur in the coombes[62] of Sussex and the Cotswolds, in the Bournemouth chines[63] and Yorkshire Wolds,[64] in Oolitic rocks in Bromptondale and in Permian breccias and Bunter sandstone in Nottinghamshire; in the *Muschelkalk* of Württemberg and the Swabian *Malmkalk*[65]; and in porous sands and gravels in the Fläming (*Rummel*), Lüneburger Heide and in other districts of west Germany[66] and of Holland.[67] Of like significance were the frost cracks in permeable Cretaceous sands in central Germany.[68] Diminished evaporation, resulting from low temperatures, also enlarged the streams and rivers.[69]

Blockfields (see p. 574) are found outside the present polar regions, e.g. in Scotland[70] (Ben Nevis, Skye, Morven, Galloway), German Mittelgebirge,[71] Pyrenees,[72] Spain and Calabria,[73] Carpathians,[74] Rila Mountains,[75] and in the White Mountains[76] of New Hampshire and the St. Francois Mountains of Missouri.[77] These more southerly accumulations are sometimes being slowly added to under present conditions[78] but generally are "disharmonic features",[79] a type of *Relictenboden*[80] or "dead" or "fossil" landscape[81] which results in a "polygenetic topography".[82] They were produced periglacially[83] when the mountains lay within the infranival zone (their fossil character is sometimes denied[84]) and low temperatures and lack of vegetation favoured them. Their analogues in arctic lands to-day, their nearness to the Pleistocene ice, and the great distance to which blocks have been carried are suggestive. Positive proof is provided in certain localities by their relationship to moraines,[85] e.g. in the Riesengebirge, and by their burial beneath loess,[86] as in Silesia (Zobten), the Black Forest, Teutoburger Wald and the lower Rhine valley, beneath peats which pollen analyses show range backwards to the close of the lateglacial,[87] or beneath postglacial soils[88]: in the basalt landscape of Hessen the blocks have a protective rind (Ger. *Schutzrind*; *Wüstenlack*) of leather-brown or reddish-brown colour which was produced in Würm times. Some may have arisen by nivation as the plateau ice contracted.[89]

Periglacial aeolian action was widespread in Europe at each glacial stage.[90]

River-ice. Large or striated stones in the terraces of valleys which may head in or be unconnected with glaciated territory also prove the climatic severity of the periglacial zone. The stones, delivered possibly by solifluxion,[91] were carried by drift- or anchor-ice and were striated in transport or in ice-jams; examples occurred in Germany,[92] e.g. Neckar, Main and Rhine, England,[93] e.g. Thames and the valleys of Cornwall and the Bournemouth area, France,[94] e.g. Seine and in Brittany, in the rivers draining Belgium and Holland,[95] in south Russia[96] as far south as the Black Sea, and in the unglaciated valleys in eastern North America,[97] e.g. James, Potomac, Susquehanna and Tennessee, as well as in the lower Columbia and other valleys of the west.[98] Ice-jams, which may have carried boulders 50–250 miles (80–400 km) in Texas[99] and as far south as New Orleans, have been held responsible for the "Spokane Flood" of Washington[100] (see p. 240). Large blocks in the Pleistocene outwash, as in Switzerland,[101] were doubtless

carried by drift-ice. Flood-ice[102] (see p. 565) may have played a considerable role and diverted streams as it does to-day.

Avalanches. Avalanches, favoured by glacially oversteepened hillsides, were likewise active during interglacial times[103] and in the late stages of the final retreat,[104] especially while the ground was still without vegetation. Many screes were built up with their aid. The attendant floods may have carried some of the blocks now strewn over the valley floors.

(*b*) *Glacial Tundra*

Existing tundra. The tundras of to-day[105] lie polewards of the treeline which, as a recent monograph shows,[106] emphasises most forcibly the climatic contrast between the northern and southern hemispheres (cf. pp. 17, 167); the treeline reaches its northernmost point in North America in *c.* 69° Lat., in Europe in 70° 18′ and in Asia in 72° 40′ (Chatanga), and in the southern hemisphere oscillates between 38° 30′ S. Lat. (St. Paul) and 56° S. Lat. (Cape Horn). Tundras cover 5–6 million sq. km in the ice-free areas of Greenland and Spitsbergen, Eurasia north of the Arctic Circle, and of the Barren Lands which range as far south as 51° N. between the forests and the polar seas in North America. Their southern boundary is generally drawn along the July or summer isotherm of 10°C[107] though some writers make it coincide with the annual isotherms[108] of 0°C or 5°C; O. Nordenskiöld[109] devised a formula linking the mean temperature of the warmest month and the mean temperature of the coldest month (fig. 210). Like the treeline in the Alps (see p. 1072), it reflects in its irregularity local and orographical conditions, such as the strength of the winds and the degree of exposure.[110] Where valleys like the Yenisei, Olenek and Lena in Siberia or the Mackenzie in Canada provide shelter, the forests push northwards and islands or peninsulas of wood amidst the tundra mark favoured localities. Tundra outliers occur on high ground ("alpine tundra") or on exposed coasts ("maritime tundra"). The forest tundra (Russ. *lyesotundra*) has isolated trees or clumps or "islands" of trees.

These plains, hills or uplands, Middendorf's "ice-steppes", are treeless; saprophytes and climbers are absent as are practically all bulbous plants and parasites. Winds, solifluxion and the arctic climate help to prevent tree growth. Marshy hollows alternate with dry stony ridges and sterile and bare rock-tundras, the whole frozen hard in winter and sheeted in snow. Lichens and mosses, e.g. reindeer moss (*Cladonia rangiferina*), abound, helped by the humus which the cold and impenetrable ground encourage to form. Perennial herbs are the commonest plants but grasses, sedges and other dry land associations thrive on sandy moraines and boulders, and low bushes, dwarf birch, willow; juniper and conifers live in sheltered spots such as gullies, especially near the southern margin. Small flowering plants, a few ferns and bog plants add to the vivid colours of greens, blues and yellows.

This vegetation, which is protected by the dry cold from bacterial and other decomposition after death, and is kept free from snow in many places by the action of wind, has adopted various means to economise water: the adaptations are a smallness of leaf, a crowding of the stunted foliage-shoots into cushion-like masses, an extensive development of subterranean organs, a wealth of flying shoots, and a common practice of producing buds near the

ground where they easily find protection through a cover of snow or dead leaves.

The vegetation is sufficient to nourish a considerable fauna, including reindeer, arctic fox, arctic hare, lemming, musk ox, glutton, ermine, weasel, vole, wolf and brown bear. These vertebrates frequent the tundras in summer, the climatic extremes necessitating annual migrations on a wide scale.

FIG. 210.—The extent of the Arctic showing tundra and ice (shaded), July temperature of 10°C (solid line), "Nordenskiöld's line" (dashes with N's), southern limit of continuous permafrost (dots and dashes), southern limit of patches of permafrost (dotted). F. K. Hare, *1903*, p. 956.

Reptiles and amphibia are rare. Conditions of life are evidently so severe that most of the molluscan species which inhabit more southerly regions in Eurasia and North America are here not able to survive. In some instances, the molluscs belong to "archaic" groups which were formerly more or less predominant in the world's molluscan fauna but have been superseded by more recently evolved and apparently better adapted forms. The hardy northern molluscs, under the uniform conditions, have given rise to few new species or varieties.[111] Other aquatic invertebrates inhabit pools and streams,[112] as in Iceland.

The Antarctic treeless zone embraces the Falkland Islands, South Georgia and Bouvet. In view of its oceanic climate and humidity, it is bounded on the north by evergreens with a definite polar limit.[113]

Tundra conditions resemble but are not identical with those which obtain in the *regio alpina*.[114]

Pleistocene tundra. That Pleistocene Europe had a similar tundra was believed by E. Forbes (1846), G. Darwin (1859), J. D. Hooker (1860), O. Heer (1864) and F. W. C. Areschoug (1869); subsequent research has justified this belief.

This *Dryas* flora consisted of numerous species,[115] such as *Dryas octopetala* (which gives the Pleistocene tundra its name), *Salix polaris*, *S. myrsinites*, *S. reticulata*, *Betula nana*, *Saxifraga oppositifolia*, *Azalea procumbens*, *Ranunculus hyperboreus*, *Armeria arctica*, *Arabia saxatilis*, *Eriophorum scheuzeri*, *Potentilla aurea*, *Batrachium aizoides*, *Polygonum viviparum* and arctic-alpine mosses, e.g. *Hypnum exannulatum*, *H. fluitans*, *H. irifarium*, *H. sarmentosum*, *H. stellatum*, *Distichium capillaceum*, *Scorpidium scorpioides*, *Tortula ruralis* and *Timmia norvegica*. It also contained Alpine species, e.g. *Saxifraga aizoon*, *Primula auricula* and *Statice montana*, which ranged northwards.[116]

This flora, some typical species of which are reproduced in fig. 211, is preserved in tufas[117] but more commonly in the "*Dryas* clays" (*Dryaslera*[118]). These light grey, plastic and finely laminated clays were deposited in basins in the drift, as they are to-day on the floor of Torne Träsk (see p. 1074) and other Scandinavian lakes within the Arctic Circle, e.g. in Lapland and Jämtland and the Dovre of Norway.

This "glacial" flora was first discovered in 1870 from macroscopic remains in Scania by A. G. Nathorst,[119] whose long sojourns in Spitsbergen enabled him the more readily to recognise its distinctive members and led him to search for this evidence. The flora grew over north and central Europe to a line running through the Pyrenees, Alps, north Balkans and Russian steppes, though in the southern localities only at higher levels. Thus it has been found in at least 65 places in Scania[120] and in very many others in Scandinavia[121] (cf. list, with literature[122]), Finland,[123] about Leningrad,[124] Denmark,[125] Germany[126] (from Schleswig-Holstein and the Kiel Canal to Saxony, Baden and Swabia), Poland and Galicia[127] and central and southern Russia[128] (with a cold algal flora). It spread on the east to the Urals and into the midst of the Siberian steppes[129] and to 500 km from the ice-edge on the banks of the Irtysh near Tobolsk[130]; on the west to the Netherlands,[131] Scotland[132] (Edinburgh, Crianlarich, Fife), England[133] (Huntingdon, Holderness, Bovey Tracey, Isle of Wight, Lea Valley), Isle of Man[134] (Ballaugh, Kirk Michael) and Ireland[135] (Ballybetagh, Co. Dublin; Dunshaughlin and Ratoath, Co. Meath; Mapastown, Co. Louth; Ralaghan, Co. Cavan; Ballyconnell Bay, Co. Sligo; Killough, Co. Down); and in the south to many Swiss localities[136] in cantons Zürich and Luzern. North Italy had apparently no tundra (see pp. 1379, 1385); for not a single arctic-alpine fossil plant has been unearthed at the southern foot of the Alps[137] though such plants have been collected from the Abruzzi. *Arctostaphylos uva-ursi* and *Empetrum nigrum* grew in south Spain.[138]

The vegetation of the Oldest and Older Dryas periods of Zone I which preceded the Alleröd oscillation (see p. 1431) was alpine rather than arctic[139]; ericaceous plants were less common and grasses more plentiful than in the

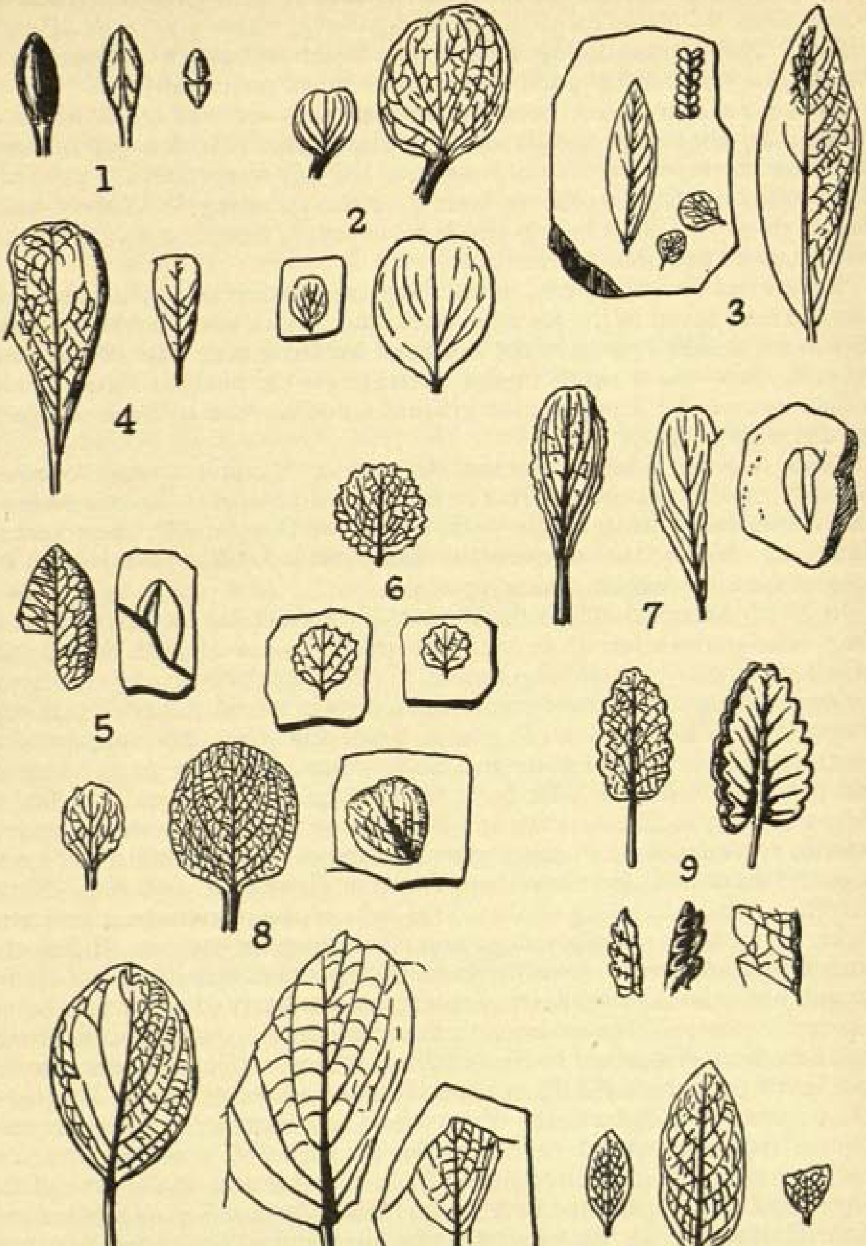

FIG. 211.—Some typical species of the Dryas flora. 1, *Loiseleuria procumbens*; 2, *Salix polaris*; 3, *S. hastata* (left with *Dryas octopetala* and *Betula nana*); 4, *Arctostaphylos uva-ursi*. 5, *Polygonum viviparum*; 6, *Betula nana*; 7, *Salix retusa*; 8, *S. herbacea*; 9, *Dryas octopetala*; 10, *Salix reticulata*; 11, *S. myrtilloides*. C. Schroeter & O. Tschumi, *1918*, p. 23, fig. 5.

arctic tundra and *Artemisia*, *Helianthemum*, *Hippophaë* and *Rumex* were typical. The pollen associated with the Hamburgian gave the following percentages[140]: *Salix* 17–51%, *Betula* 43–80%, *Pinus* 3–21%, NAP 148–346%. The corresponding figures for Stellmoor were[141]: *Salix* 19%, *Betula* 47·5%, *Pinus* 32% and NAP (non-arboreal pollen) 269%.

In the Younger Dryas period there was a newer rise of NAP and of *Selaginella*, *Hippophaë* and *Artemisia*. The treeline was 800–900 m lower than now corresponding to a depression of the July temperature of 7–8°C.[142] The pollen of the Ahrensburg layer gave the following[143]: *Salix* 5–20%, *Betula* 50–70%, *Pinus* 18–44% and NAP 66–171% (see p. 1071). *Empetrum* characterised this period in Holland.

In east and central Siberia, under the greater anticyclone then prevailing, there existed south of the ice a broad tundra, farther south a forest tundra, and in the middle courses of the Lena and Yenisei a taiga zone.[144] In west Siberia, there was a shrub tundra alternating with birch-fir forest tundra which east of the Urals passed gradually into a warmer forest-steppe[145] (cf. fig. 293, p. 1380).

Sorex ananeus, *Mustela erminea*, *M. nivalis*, *Microtus agrestis*, *Saxicola oenanthe*, *Anthus pratensis*, *Cervus corax*, *Aegialitis hiaticula*, *Lacerta vivipara* and *Salmo trutta* lived in the western strip of Denmark[146] where certain forms, e.g. *Margaritana margaritifera* and *Cidaria pupillata*, survived to the present from the last interglacial epoch.

In North America, outside the Wisconsin ice-sheet, lay the prairie flora to the west, Ozarkian forests to the south-west, the coastal plain flora in the Mississippi valley, deciduous forests in the Appalachian and piedmont regions of the south-east and coniferous forests in the north-east.[147] A cold climate flora (*Picea mariana*, *P. glauba*, *Tsuga* and *Abies*) was widespread in Pleistocene New Jersey; white and black spruce, fir, white pine, tamarack and paper birch lived not far from the ice-edge in Minnesota[148]; relics of these trees, e.g. in Illinois, Ohio and Indiana, with their characteristic undergrowth, occur far south of the southern border of conifer dominance[149]; and pollen of *Picea* and *Abies* have been found in Pleistocene deposits in North Carolina. Some lowering of altitudinal belts in the mountains is indicated which permitted a southerly migration of northern vegetation. Relics of a tundra flora are rare[150] (possibly because deposits examined do not go far enough back, the tundra was fragmentary and transitory[151] or the bog-basins retained masses of stagnant ice until the surrounding country was ice-free); they have been discovered in New England (mixed with non-tundra species) and Maine (with high NAP), in varves in Massachusetts, and in lateglacial lake-deposits in Connecticut. Yet podsols, characteristic of tundra conditions, were widespread over northern Michigan[152]; a varied flora, resembling that of to-day, lived in the Lake Superior area at the time of the Nipissing Lakes[153]; and the flora in the Prairie Terrace (see p. 1260), north of the Gulf of Mexico, contains trees which are limited to-day by the mountains of New England.[154] In harmony with this were the incipient solifluxion,[155] with periglacial involutions (*Brodelböden*), in Illinois (Cary substage), Connecticut and New Hampshire; the frost-thaw basins of New Jersey and ice-wedges[156] of Montana, Illinois and Rhode Island; and the blockfields and fossil stone-streams[157] in Pennsylvania and the Driftless Area of Wisconsin. These features give near the ice-border a mean annual temperature of −3·3°C[158]—the mean July temperature may have been about

10°C.[159] Generally speaking, however, possibly because the margin of the ice-sheet lay 10° of latitude farther south than in Europe, the tundra zone seems to have been very much narrower in North America than in Europe—the modern flora and fauna immigrated astonishingly early (see p. 1412)—though mound-relief systems of the Gulf coastal plain have been interpreted as palsen.[160] The sub-arctic forest was generally close to the margin of the ice-sheet so that the abundance of forest tree pollen masks the evidence of the tundra, and the plains of the interior allowed a free sweep of winds from the south-west. How close to the ice the deciduous forest persisted depended, as in Europe (see p. 1077), upon the diversity of the relief.

Trees probably grew within 80 miles (*c.* 130 km) of the ice-edge in eastern North America but farther away near the coast because of the greater cloud and wind there and of the "cold wall" off the New Jersey coast. The narrowness of the zone in general compared with Europe was connected with the more rapid southerly rise of the average summer temperature (Manley, 1955) (pl. XXVIB, facing p. 913).

The climatic fluctuations of later (Wisconsin) age are revealed by frontal moraines (see ch. XLII), by overridden lake-deposits (see ch. XLII), by low-water phases, e.g. the Two Creeks interval (see p. 972), by weathered drifts (see p. 969), by pollen profiles (see p. 1175), by fossils in marine sediments (see p. 1309) and by periglacial features.

Range of arctic life. The wide distribution of the arctic and alpine animals in Europe (see ch. XXXIV), e.g. *Elephas primigenius*, *Tichorhinus antiquitatis*, *Rangifer tarandus*, *Cervus megaceros*, *Ovibos moschatus*, *Gulo luscus*, *Lepus variabilis*, *L. arcticus*, *Dicrostonyx torquatus*, *Lemmus lemmus*, *Marmota marmota*, *Sorex vulgaris* and other members of the fauna of the "rodent layers" (see p. 1036), likewise indicates the coldness of this tundra, though these animals spread much farther than the arctic flora which alone fixed the limit of the arctic climate. They lived on the sites where the remains are now found: young and adult animals are mingled in innumerable places and milk teeth of arctic fox, lemmings and other species have been discovered. The herbivores among them are the most delicate climatic indicators since carnivores possess great adaptive powers, respond slowly to change, and do not directly depend upon the vegetation (see p. 903).

The severity is attested too by the southerly range of numerous creatures, e.g. the polar bear, *Ursus maritimus*, as in Scania[161]; arctic coleoptera in Scania and Denmark[162]; the phyllopod, *Apus glacialis*[163] (now confined to icy pools and lakes near the glaciers of Greenland, Spitsbergen and Norway) in the Isle of Man, Scotland, Denmark and Scania; arctic molluscs,[164] as near Weimar and in Westphalia and in the region of the Alpine glaciation; arctic *Pisidium* from north Europe in the environs of Geneva[165]; arctic fish in south Bosnia[166] and salmon (*Salmo trutta*) in the Mediterranean region[167] and in breccias in central France[168]; seals (*Phoca hispida* and *P. groenlandica*) in the Aurignacian rock-shelter of Castanet (Vézère) and the late-Magdalenian cave of Raymonden and in the drawings of palaeolithic artists in south France[169]; northern birds in lateglacial clays and deposits[170] in Sweden and south France (but not in Portugal, south Italy, Corsica or Sardinia, or the southern Mediterranean[171]) and in south Russia[172] (polar lark, white partridge, grouse and chough, with arctic fox and northern deer); the ptarmigan, *Lagopus mutus*, in almost all European caves,[173] and with the black grouse, *Tetrao tetrix*, in numerous caves as far south as Italy and Spain[174]; the two grouse of Jersey,[175]

the wild goose, *Anser palustris*, of Salisbury,[176] *Lagopus albus*, with *Lagopus mutus*, the characteristic bird fossils of the European Pleistocene caves,[177] in central Europe, Monaco and north Italy, 15° farther south than now (arctic grouse formed 90% of the large quantity of birds found in Peterfels[178] and nearly 3000 individuals were dug out of one cave near Budapest[179]); the snowy owl (*Nyctea nivea*), with chamois, ibex, arctic hare and glutton, on the island of Palmaria in the Gulf of Spezia[180] and plentiful in the Dordogne (Astre, 1950); the alpine chough (*Pyrrhocorax pyrrhocorax*) and red-billed chough (*Pyrrhocorax gracilus*) found in the Crimea and at Gibraltar, Grotte de l'Observatoire and Grimaldi caves[181]—at Gibraltar there also occurred the great auk and ibex[182]; *Alca impennis* (which is found in pre-historic kitchen-middens and became extinct in 1844[183]) in the Channel Islands, at Gibraltar and in south Italy,[184] e.g. Romanelli cave in Apulia—upper palaeolithic representations of it occur near Santander[185]; and other boreal species—on the plains of Italy northern deer replaced the fallow deer, wolf the jackal, hare the rabbit, and the small horse, *Equus hydruntinus*, the larger horse.

Hare and red fox, two species typical of temperate Europe to-day, and ibex, auk, barnacle goose and the lesser white-fronted goose from north Europe, were abundant in the Grotta Romanelli near Castro in southern Apulia[186]; they probably implied a continental climate with cold winters.

North America, compared with Europe, had relatively fewer gallinaceous birds and a higher number of birds which are now extinct.[187]

Central European corridor. Great cold characterised the corridor between the Scandinavian ice and the smaller glaciations of the Alps and Carpathians which narrowed from *c.* 300 km in the west to practically nothing where the Scandinavian ice pressed against the Carpathians. To the primary cooling were added local, secondary effects due to the proximity of the ice, anticyclonic ice-winds, cold waters from melting snows in spring and summer, glacier-streams (those of Mount Hood and Mount Shasta in North America to-day affect the temperature of their valleys[188]) and drift-ice and melt-waters off west Europe.

Some authorities[189] restrict the cold to the immediate margin: the tundra was an "ice-margin flora" (*Gletscherendenflora*). They advance the following arguments: the rest of the corridor had an oceanic climate and coniferous and northern deciduous trees whose pollen is only absent from the *Dryas* clays (see below) because it was subsequently destroyed[190] (an explanation quite unjustified[191]); the arctic species are not truly arctic[192] but highly specialised plants which civilisation, competition and climatic change have driven northwards[193]; the large size of the Pleistocene mammalia (see p. 798) and the abundance of their remains indicate better conditions than in the Holocene[194]; the dwarf birch, as in Bovey Tracey, was washed down from higher ground[195]; the water- and moor-plants demand a mean June temperature of 5–6°C[196]; current ecological conditions are the key to the distribution of the arctic relics[197]; many alpine plants live also below the treeline and *Dryas octopetala* itself in west Ireland at sea-level; spruce and other trees were included in the flora (see p. 1077); many molluscs survived, as in central Germany[198]; and the arctic lepidoptera, at the end of the Glacial period, withdrew not into the Alps but into the Arctic.[199]

Yet most workers,[200] following Nathorst,[201] believe that the tundra was wide and carpeted the whole corridor (so far as this was not completely

barren), the periglacial zone having a width[202] computed at 200–300 km and during the Würm glaciation of 200–250 km or even 500 km: the *Dryas* flora of Deuben and Luga in Saxony was at least 70–75 km from the ice-edge, of Borna 100 km and of Quakenbüsch (Hanover) and Twente (Holland) even more, and the lower limit of solifluxion was at sea-level.[203] The tundra in Riss times in Poland was more than 100 km wide.[204] These writers point to the occurrence of forests of *Picea excelsa*, *Pinus sylvestris* and *P. montana* towards the close of an interglacial epoch at Cannstadt,[205] to the widely distributed tundra plants and animals (see above)—to-day *Dryas octopetala* extends in Greenland and Spitsbergen to 79° N. Lat. and *Betula nana* requires more than 30 days with a maximum temperature of 10°C[206]; to the arctic birds,[207] e.g. *Lagopus albus* and *L. alpinus*; and to the permafrost, with its solifluxion and kindred features (see above), which was inimical to tree growth.

Even the plains were above the treeline,[208] that is, the discontinuous line marking the extreme occurrence of individual trees. Pollen of pine and other trees is absent from the glacial moors of central Germany[209]: the absence of forest has been proved for the climatically favoured inner Bohemian Elbe basin[210] and for the Rheinpfalz[211] which was *c.* 475 km from the edge of the Scandinavian ice, 210 km from the nearest Alpine glacier and over 100 km from the glaciers of the Vosges and Black Forest. This absence is notwithstanding the long distances to which flying pollen is now being carried by the wind[212]: pollen occurs in the upper air[213] in the Arctic, over the North Atlantic 1000 km from land and over North America (up to 11,000 ft or 3350 m); in the snows (*Podocarpus*) of the South Orkneys[214] (from South America), of Adélie Land and Ross Quadrant[215] (bacteria), and on the Chatham Islands[216] (*Podocarpus* and *Dacrydium*), 700 km from New Zealand; in the ice of Alpine glaciers[217]; in recent moors in Novaya Zemlya,[218] 600–800 km from the nearest trees in north Russia; species of *Picea* and *Pinus* in peats of south-west Greenland[219] (carried 960 km from North America); in the treeless Faeroes[220] (*Pinus*, *Alnus*, *Betula*, *Corylus*, *Tilia*), derived from Norway (*c.* 585 km), Iceland (*c.* 430 km) or Scotland (420 km). Non-tree-pollen (NTP) show that much of central Europe, including central Bohemia at 180 m A.S.L., was above the limit of dwarf bush heath[221] (*Zwergstrauchheide*). Even in lateglacial time the timberless belt extended in zone I from Germany to Gotland and south-west Norway, and in zone III from Denmark and Bornholm to central Sweden.[222] There was an absence of tree pollen from Schussenried.[223]

During zones I and III[224] (see p. 1066) there were high *Salix* and *Hippophaë* values, and in Lake Constance area 30–40% of the NAP pollen was *Artemisia*.[225] During zone III the treeline was 800–900 m below the present treeline in the Harz, and 900–1100 m in the Vosges and west Lake Constance area,[226] and closed woods existed in the upper Rhine rift-valley, in inner Bohemia, in the Pannonic basin and in Lower Austria.[227]

That a forest zone was missing is attested too by the snowline which was depressed by about 1200 m at maximum glaciation in the Alps (see p. 652). The treeline must also have been depressed since that line is to-day separated from the treeline by a considerable interval which varies, like the treeline itself,[228] according to the sum of the local climatic factors and is least where the climate is moist, e.g. *c.* 457 m in Alaska and Patagonia,[229] 800–1000 m in the Caucasus and Hohe Tatra,[230] 900–1000 m in the Karakoram,[231] and

700–800 m (500–980 m) in the Alps[232] (cf. map[233] of the Swiss treeline of to-day where, as in the Arctic, deciduous trees form the treeline in the more oceanic climate and conifers in the more continental climate[234]). Representative figures are 1000–1160 m in Germany[235] and 1300 m in Switzerland[236]; in south-west Germany, *Pinus montana* was limited by 400–500 m and *P. excelsa* by 200 m.[237] Lateglacial layers in the moors of west Transylvania at 290 m and 356 m prove a lowering of the treeline by *c.* 1300–1500 m—the glacial climate of the Hungarian plain was roughly that of the present mountain climate at *c.* 2000 m[238]—though *Pinus sylvestris* lived during the last glaciation in the Pannonic basin and *Picea excelsa* in Bulgaria.[239] At Forli, south of Ravenna, in the Plain of Lombardy, where thin pine forests (*Pinus sylvestris, P. montana*) grew at 40 m above sea-level (see p. 1385), it was depressed even more. Boreal mosses and alpine diatoms have also been discovered in the Plain of Lombardy.[240] Near Pisa, a subalpine forest of pine (with *Picea, Abies* and *Betula*) has been found below present sea-level (−23 m), and *Abies, Pinus, Picea* and *Alnus* grew in the Pontine Marshes[241] in harmony with the occurrence of glaciers in the Apuan Alps and a depression of the treeline by more than 900 m. The vegetation zones were lowered in the Cevennes.[242] The position of the treeline in Europe at the Würm-Weichsel stage, which was determined by the July isotherms, is suggested in the text-figure[243] (fig. 189). In the oceanic west, it lay in general east of the Rhine but in the cold area of central Europe was displaced south of the Alps and farther east was thrust northwards to Moravia and the Carpathians. In Italy and Transylvania the glacial and lateglacial forest-limit descended to a greater extent than did the glacial snowline.[244]

According to J. Büdel,[245] the 10·5°C July isotherm (= polar treeline) ran from the western end of the Pyrenees south of the Central Plateau, through the Alps and Vienna to south of Moravia, to the upper Dnieper and Volga—at the Atlantic coast it was 1000 km from the ice-edge, in the Volga the two almost touched. South of this line was loess steppe, north of it loess tundra, and along the ice-edge a *Frostschutt-tundra*.[246] West Europe including France had a forest tundra. Immediately outside the ice-front there was no tundra vegetation because of winds and melt-water streams.[247] H. Poser and J. Büdel have reconstructed the climatic provinces of Europe during the last-glacial epoch (see p. 957).

Corroborative are the nature and the similarity of the loess molluscs[248] (see p. 524); the occurrence of *Valvata pulchella*, a northern form, in the Rhine valley at Mannheim[249] and of tundra plants at Nancy (Lorraine) and near Freiburg-im-Br.,[250] of cold insects in places[251] between Galicia and Denmark, and of dwarf birch below 200 m in Württemberg[252]; and the mingling and interchange of arctic and alpine plants on the plains of central Europe[253] (Ger. *Florenmischgebiet*), especially where the corridor was narrow. The glacial mixed fauna included cold stenothermal fish, e.g. *Salmo trutta*.

This theory of a broad Pleistocene tundra, and a mingling of arctics and alpines was suggested by O. Heer[254] 24 years before Nathorst first found fossil arctic plants in Scania (see above)—as we have already mentioned (see p. 1066) J. D. Forbes, C. Darwin, J. D. Hooker and others had previously anticipated the exchange. The theory was substantiated by the discovery of arctics and alpines together in glacial deposits, as at Borna in Saxony (see p. 1084), by their relics in central Europe,[255] including the *Betula nana* of an occasional locality in Germany, and by the presence (according to their

powers of adaptation and competition) of alpines in the arctic tundras and of arctics in the Alps, Pyrenees, Carpathians and German Mittelgebirge. The occurrence of *Larix decidua*, *Pinus cembra*, *P.* cf. *montana*, *Abies alba* and cold-loving mosses suggests a cold, moist climate for Hungary.[256]

The mingling of these arctics and alpines, which in the main took place from north to south and not vice versa, was doubtless facilitated by the glacial streams,[257] including the *Urstromtäler* along which *Thymallus thymallus*, *Cottus poecilopus* and *Leuciscus leuciscus* probably wandered; this is demonstrated by such streams in Siberia, British Columbia and Patagonia

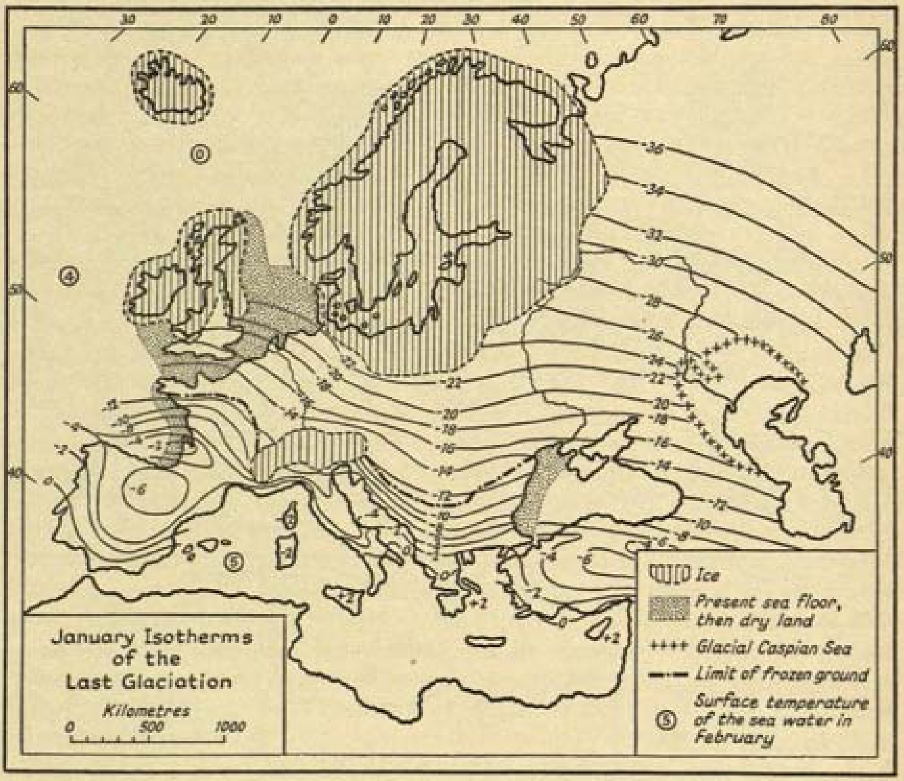

FIG. 212.—January isotherms of Europe during the last glaciation. The equatorial limit in France lay along the isotherm of $-4°C$. The Adriatic was dry land to the position of the $-4°$ isotherm. F. Klute, *Erdk.* 5, 1951, p. 273, fig. 1.

to-day[258] and has a parallel in the changes brought about by man by the construction of canals. The boreo-alpine pattern of some genera suggests multiple glaciation.[259]

These distributions and relationships point to harsh conditions[260] with short false summers and temperatures well below 10°C. The fall in the annual temperature has been computed at 5–6°C for Switzerland[261] and at 5·5°, 8° or 10–12°C for Germany[262]—the glacial molluscs in the Main valley resembled those of present-day Leningrad. Solifluxion features register equal falls[263] (9°C)—the southern limit of the permafrost lay on the mean

annual isotherm of $-2°C$ (see p. 563)—as do comparisons with the temperatures in Greenland[264] (10–12°C) and at Torne Träsk[265] where typical Dryas clay is now accumulating (10–12°C). The temperature in Thuringia has been likened to that of the lower Petschora to-day. The mean annual temperature may have been 2° to $-2°C$[266] or, on the basis of the loess mollusca, 5°C.[267] The mean winter temperature in central Europe and the east Alpine foreland has been estimated at $-12{\cdot}7°C$[268] and the mean annual temperature on the Swiss Plain at 3–4°C.[269] The January isotherms have been reconstructed as in the text-figure[270] (fig. 212): the *Urstromtäler* had

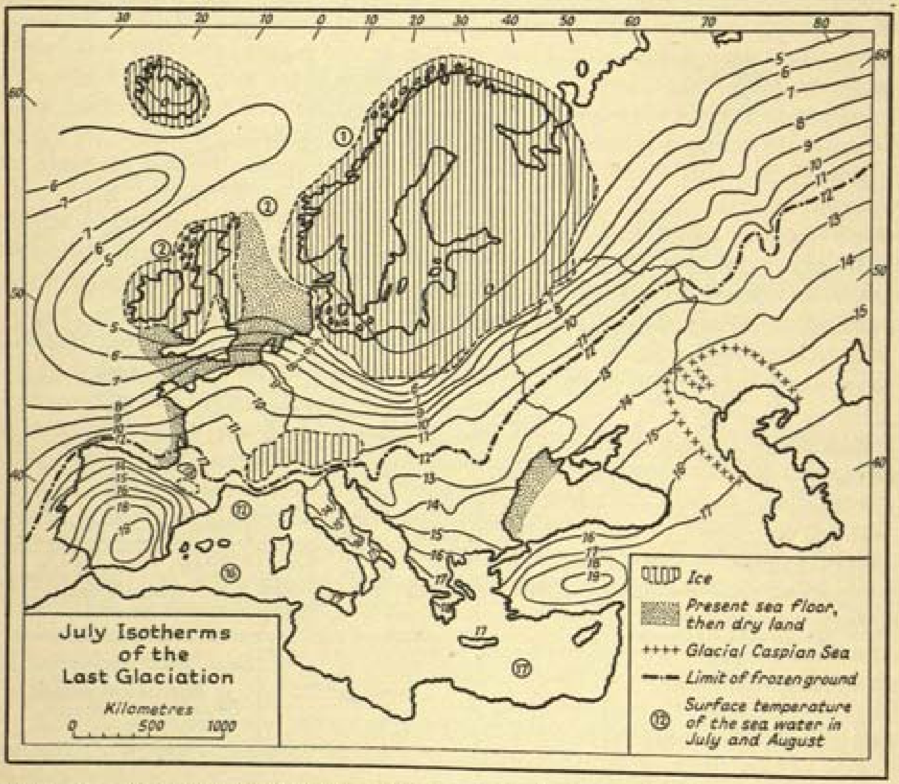

FIG. 213.—July isotherms of Europe during the last glaciation. F. Klute, *Erdk.* 5, 1951, p. 274, fig. 2.

little water in winter.[271] The mean summer temperature[272] has been estimated at 9·3°, 8·7° or 8°C or as low as 3°C. The July temperature[273] was 4·4°C or below 10·5–11·0°C and at Starunia (417 m) was 10–12°C. Rather cold summers in Denmark are suggested by the slight depth of the thaw-layer[274] (cf. p. 1062). The conditions in north Germany have been compared with those of Vatnajökull to-day.[275] The July isotherms of the last glaciation have been reconstructed as in the text-figure[276] (fig. 213). The summers were short and the winters long and cold.[277] "Day-varves" (see p. 1155), which record the minimum number of days when glacier-streams were flowing, have also been used for this purpose[278]: those at 400 m in the

Eulengebirge, laid down shortly before the maximum of glaciation (Elster), suggest that for about six months the mean temperature was more than 0°C and that the mean annual temperature was at least 4° or 3°C lower than now. Nevertheless it has been said that the summer was continental and its temperature as high as 15°C or more[279] and that the tundra was not arctic but subarctic[280] as in modern Iceland, especially in the more oceanic west where snow covered the ground for almost half the year. In any case, care has to be taken in comparing the temperature conditions in present arctic latitudes with those which reigned in the more southerly latitudes of Pleistocene central Europe[281] (see p. 1061).

The fossil frost soils of periglacial Europe reveal distinct climatic differences[282]; ice-wedges, which require a temperature of below −10°C for their formation, were apparently more frequent in central and east Europe, which had a continental climate, and especially about the "cold pole" of the corridor in central Germany, where the mean January temperature was −14° or −15·3°C[283]; and solifluxion and similar soils occurred chiefly in France and England which had plenty of snow and not too severe winter cold. The temperature fell northwards: the leaves of *Dryas octopetala* were smaller in north Germany than in Starunia.[284]

Precipitation too was probably less,[285] both in winter and in summer—it amounted annually to 300–350 mm but decreased towards the ice and eastwards. This agrees with the following: the present conditions at Torne Träsk; the periglacial loess; the flora's xeromorphic nature[286]; the *Citellus rufescens* of north Jutland[287]; and the absence from late-Pleistocene deposits in the north Alpine region of *Alnus viridis* (which requires much moisture[288]) and of frost-susceptible plants which need snow protection.[289] A. Klein[290] has reconstructed the precipitation in western Europe during the last glaciation in percentages of the present precipitation (fig. 214). Most rain probably fell in spring and autumn.[291] The continental climate was intensified as the ice-sheet grew and gradually extended westwards into western Europe to carry loess conditions westwards too. The presence of steppe has repeatedly been emphasised[292] (see p. 526). Nevertheless, greater precipitation than now has been suggested for central middle Europe[293] while the greater snowfall in the west is indicated by the chianophilous plants in the lateglacial flora of Ireland and the abundance of *Salix herbacea* in Jaeren, south-west Norway (Faegri, 1953).

The tundra was more favourable than the modern one because both latitude and altitude were lower—the insolation therefore was higher, the seasonal and daily rhythm of life was different[294] and the climate was glacial rather than arctic.[295] The zone was also much broader. As in Russia to-day,[296] it shaded into and mingled with the steppes of the drier places—species of the two are found together.[297] Steppes and tundras alike have intense winds, dry air, scarce and irregular precipitation and recurring cold spells[298]: the short period of vegetable growth in the tundra is due to lack of warmth, in the steppe to lack of moisture. The present plant distribution compels us to believe that a steppe element lived in central Europe during the Glacial period. Thus the halophytes *Blysmus rufus* and *Crambe aspera* lived in Galicia.[299]

During the Early Dryas period (Hamburg stage), the tundra period proper, there lived *Gulo gulo* and *Desmana moschata*, and during the Late Dryas period (Ahrensburg stage), *Lynx lynx*. Denmark at this

stage had *Rangifer tarandus*, *Gulo gulo* and *Bison*, with a rich vegetation of Gramineae, Cyperaceae, *Artemisia* and here and there willow and birch.[300]

True cave-forms were unable to survive,[301] either here or in the German Mittelgebirge, since the temperatures were too low, guano was absent and wood with fungi was not swept into the caves from the surface. Hibernation was also probably difficult, though reindeer, arctic hare and musk ox no doubt stayed the whole time, passing the winters in the protected entries of the mountain valleys. The lacustrine fauna, if we may judge from present-day Spitsbergen, Bear Island and Franz Josef Land (in which the species of Entomostraca are 15, 10 and 2 respectively), was also probably poor in species.[302] These were probably cold-tolerant and either ubiquitous

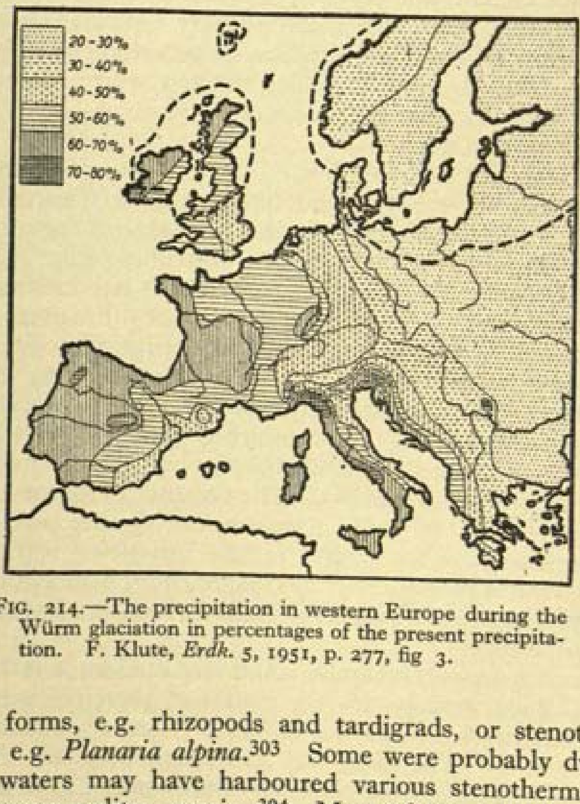

FIG. 214.—The precipitation in western Europe during the Würm glaciation in percentages of the present precipitation. F. Klute, *Erdk.* 5, 1951, p. 277, fig 3.

eurythermal forms, e.g. rhizopods and tardigrads, or stenothermal cold-water forms, e.g. *Planaria alpina*.[303] Some were probably dwarfed. The glacial melt-waters may have harboured various stenothermal forms and eurythermal cosmopolitan species.[304] Most of the inhabitants of springs also survived.[305] The fact that some of the freshwater creatures lived on suggests that the streams and lakes were not completely frozen[306]; of the 56 species of freshwater fish in Germany 25 are regarded by A. Thienemann[307] as members of the glacial fauna. He also thinks many freshwater molluscs and even some Tertiary cave invertebrates, e.g. *Niphargus*, survived in the corridor and that purely arctic freshwater invertebrates lived along the edge of both the Scandinavian and Alpine ice-sheets, together with other northern forms which still live in central Europe; the narrow zones of cold arctic and alpine freshwater forms margined the broad zone of the mixed

fauna. Birds with boreo-alpine distribution may have lived in central Europe,[308] as may *Dreissenia polymorpha*[309]: remains of the latter have been found in interglacial deposits and in the Memel delta.

The biological conditions were not everywhere quite uniform: the great latitude range makes this certain for European Russia. In the corridor itself not only grasses and sedges ("grass-sedge tundra") but genera like *Artemisia, Hippophaë, Helianthemum, Rumex* and *Thalictrum*, which have central European rather than arctic affinities, survived.[310] More favourable conditions, resembling those of modern Iceland, existed towards the west (see above), with low shrubs and plentiful animals, e.g. *Saiga tatarica, Allactaga* and *Marmota*. Steppes, heaths and forests were not successive but neighbouring formations, controlled by topographic and edaphic factors. Nor were forests and woods entirely lacking[311]—Nehring spoke of a *Waldinselsteppe* and tree pollen have occasionally been found in the loess.[312] While the dry cold of the summer months prevented the growth of trees on the open plains, xeromorphic dwarf bush heaths or meagre forests of the taiga type persisted on gravelly hillsides and where no opportunity offered for solifluxion, as in sheltered localities, along stream courses (analogous with those in north Siberia described by Middendorf, Pallas and many others), e.g. in the sheltered entries and valleys[313] of the Mittelgebirge, of the Main, Neckar and upper Rhine, of Bohemia, Hungary and the Carpathians and the uplands of south Poland, where the animals probably spent the winter. Thus while the carbonised wheat grains (*Triticum compactum*) in a rodent layer in Lower Austria may have been carried thither by winds,[314] the small firs used in the fires of loess man in Lower Austria were probably growing locally. The diploids of *Biscutella laevigata* in certain German valleys are thought to be relics of temperate plants which survived.[315]

Consideration of the relationship between treeline and snowline suggests that deciduous forests clothed the slopes of the east and south Carpathians,[316] especially those which faced south, though the widespread loess proves that forest was absent from the whole of south Russia except the Crimea (see pp. 1031, 1383). Pollen of *Abies, Picea, Pinus sylvestris* and *P. pallasiana* has been found in the east Carpathians,[317] birch in Bohemia and the western Carpathians,[318] and other trees east of the Alps.[319] The fossil orthopterous fauna of Starunia suggests a country of meadows dotted with bushes.[320]

According to F. Firbas,[321] north of the Alps there probably survived *Betula pubescens* and *B. pendula* since these tree birches occurred in Alleröd times. *Pinus montana* lived in south Germany even in the lowlands and *Populus tremula* also probably survived.

Forest animals, e.g. *Cervus elephas, C. alces* and *Bison priscus*, lived on the glacial loess.[322] Pine, birch and willow grew in the Erzgebirge,[323] oak and birch at Krain,[324] fir at Borna near Leipzig,[325] and larch in Silesia and Galicia and with cembra-pine at Ludwinow near Cracow.[326] Oak trunks are found in Swiss moraines at Kaltbrunn near Uznach[327] and fir and pine in the thick loess of Hundsteig in Krems.[328] There is evidence of forests at Mauer[329] and of grass steppes at Mosbach.[330] The oldest known deposits in the Rhine rift-valley contain water and marsh plants (*Ceratophyllum demersum, Cladium mariscus, Carex pseudocyperus*) and belong to a birch-poor fir period.[331] Because the Würm loess does not ascend the slope of the Black Forest as high as the Riss loess, it has been suggested that during Würm time a narrow forest belt skirted the slopes.[332] Tertiary insects and other faunal forms may have

survived in favoured localities in central Europe[333] though most were driven out.

Although not all the occurrences mentioned above date from the colder phases, they warrant the view that some trees found asylum in the "vegetation islands" of many parts of central Europe, namely, fir and kindred trees in the north and oak in the south-west.[334] In this connexion, it should be remembered that species already established, whether floral or faunal, when subjected to gradual climatic change persist under conditions that would successfully prevent their introduction.

The very early appearance of fir forests in the upper Rhine plain[335] at the close of glaciation also suggests that there were relics west of the Alps,[336] and the distribution of *Hydraena dentipes* as far north as the edge of the ice shows that this beetle survived.[337] *Bathynella natans*, related to the Australian Anaspididae and found in deep wells at Prague and Basle,[338] also persisted, as did many Lepidoptera and Coleoptera[339] which include steppe relics dating from these times. At the western foot of the French Alps and Jura and in the Hungarian plain, Vienna basin and East Carinthia, they display a richness in species, numerous endemic forms, and isolated genera and species known elsewhere only from central Asia.

The following zones, compressed by the ice-sheets into a narrow space, may be distinguished in the corridor[340]: (1, 2) tundra and alpine meadows in the mountains; (3) forests near the mountain foot, in river valleys and on south and west slopes; (4) loess steppe; and (5) tundra and *sandur* bordering the ice-sheet. The limits of these zones, especially those on the south, are not definitely known, though F. Firbas has attempted a map of them.

The northern limits of the various invertebrate groups, especially the Entomostraca, which are said to correspond to the borders of the various ice-sheets in Germany and Russia, may be related to the distances from the ice-edge, according to the stenothermic conditions under which the creatures were able to live.[341]

Although the position of the treeline is not known, forests certainly endured to a far higher degree in the "wander refuges" on either side of this vast southerly tundra penetration into central Europe. They outlasted the Glacial period in the moister and warmer south-west,[342] e.g. in France, where the Pleistocene sediments show that the periglacial climate was much less severe,[343] and especially south of the Loire and west of the Cevennes which was open to Atlantic influences, though glacial animals (see p. 1069), the flora and indications of frost and wind suggest a climate even here like that of south Alaska and central Iceland to-day.[344] Between the Loire and Garonne there existed a subarctic forest and shrub tundra and in the central plateau a forest tundra. Trees also lived in the lower Rhine, and on the Riviera coast (then wider by a strip now submerged; see p. 1269). Mediterranean relics are abundant at the foot of the west Alps and of the French Jura Mountains.[345] Confirmative are the remains of larch, fir and pine in Lorraine and of larch in central France,[346] and the postglacial immigration of silver birch, fir and beech into west Switzerland, south Bavaria and Swabia from the west (see p. 1449). Fossil leaves show that the beech, the most typical representative of the temperate climate of central Europe, was at home in central and southern France at the close of the period, and beech associations, rich in characteristic species, form well-developed climaxes in south-west and south-

east Europe. The beech grew not only in a great part of France but in Spain, Italy, Swabian Alp, south Bohemia and eastwards into Bucowina and the Balkan Peninsula.[347]

Birds also withdrew to the south-west (France and Spain) and into the south-east[348] to undergo in some instances taxonomic differentiation. When they returned they formed either a hybrid zone (speciation incomplete) or an overlap (speciation complete), as they did in North America (see p. 1378). Isolation also caused the evolution of a western species of newt (*Triturus cristatus*) and an eastern species[349] (*T. marmoratus*) and of separate forms of snails and insects at the southern foot of the Alps[350] and in central Europe.[351]

Since the snowline and treeline rose eastwards, arborescent vegetation continued in east and south-east Europe,[352] e.g. about the Caspian and Black Sea and in Poland, Galicia and the Balkans. It may have survived in the Danube valley, in the Carpathians and in the Eastern and Transylvanian Alps, though the fact that the forest development in the Pannonic basin, in contrast for example with Serbia,[353] began with a fir-birch phase as in west central Europe—other trees were absent—suggests that at best only fir and birch could have survived in these parts.[354] Taiga may have occurred here as in south France and south Siberia.[355] Pine was used for fires by palaeolithic man in Lower Austria. Scattered colonies of the karst flora, relict from the Tertiary, subsisted with the fir in the north-west Balkans.[356] Albania was a refuge.[357]

Freshwater molluscs inhabited joints, lakes, swamps and rivers in central Europe.[358] This conclusion is sustained by analogy with modern high Alpine lakes, migration after the ice-retreat into Scandinavia and the Alps, and relics on the central European plains.[359] The water fauna and flora had a richness compared with the land life. This was noted for the lateglacial biota[360] of Denmark and Scandinavia where the contemporaneous water fauna of the *Dryas* flora required a vegetative period of at least four months and a July temperature of 9°C. This contrast between a high arctic land flora and a temperate shallow water fauna and flora, also observed at Krystynopol, Galicia,[361] and in the lateglacial beds of the Lea valley[362] (see p. 1001) and of Co. Louth in Ireland,[363] has been satisfactorily explained.[364] Shallow lakes in mid-latitudes with a southern aspect and a high spring sun are warmer than the air above; this is exemplified by present-day Denmark where the difference exceeds 3°C and in Greenland whose shallowest ponds and pools have the richest vegetation.[365]

The molluscan fauna was probably richer than that yielded by the loess and aquatic beds: elements which inhabited mountain heaths, cliffs or forests and xerothermic species generally are unrepresented.[366] Whether the corridor had peat moors within it is uncertain: such formations are both denied[367] and affirmed[368] (especially for western slopes). In any case but little peat can have been formed.

Reviewing the evidence, it would seem that Europe south of the Scandinavian ice-sheet, at any rate at the time of the last glaciation, had the following climatic distribution[369] (see fig. 189). South of the ice lay a permafrost-tundra zone, glacio-maritime in the west, with summer temperatures of 10–13°C, a January temperature of 0–3°C and rains at all seasons; glacial in central middle Europe, with a January mean temperature below −14°C and east winds in the east and west winds in the west; and glacial continental in the east, with precipitation mostly in summer and a July temperature about

10°C. In the north Balkans, there was a continental permafrost forest region, and in France a maritime forest zone bordered on the north and east by a narrow maritime tundra zone without permafrost. The southern peninsulas had forests (see p. 1379), though the influence of the Glacial period in the Iberian Peninsula is seen in the spreading of *Pinus sylvestris* to the coast of Portugal[370] and the break up of the distribution of *Rhododendron ponticum*.[371] Cryoturbation, however, was missing.

Southern England. Signs of glaciation have from time to time been claimed for the region south of the limit usually assigned to the ice in England. They include striated surfaces and glaciated boulders in Somerset,[372] boulders too big to have been carried by streams,[373] glacial gravels,[374] and even boulder-clay in several localities[375] (Tiverton, Barnstaple, Watchet and Hastings) and beneath stanniferous gravels in Cornwall.[376] It is further claimed that moving ice rounded the Cornish "tors"[377]; that ice-caps crowned the Weald[378] and Chiltern Hills,[379] produced the "head" and fashioned the radial drainage by coombes on several chalk areas[380]; and that glaciers existed in the Channel Islands.[381]

These and allied phenomena (also imputed to drift-ice[382] or great floods[383]) resulted probably from the rigorous climate induced by the adjacent ice-sheet. Erratic-bearing ice drifted up the English Channel (see p. 1097) and over the Scilly Isles (see p. 778), and arctic plants grew just above present sea-level in the sheltered Cornish valley of the Teign at Bovey Tracey (see p. 1066). The Isle of Wight had a climate comparable with that of Lapland or north Russia at the present day.[384] Deep snows, with the copious precipitation and sharp frosts, no doubt buried the high ground, e.g. the Downs,[385] formed drifts in the valleys, notched out nivation hollows in Devon[386] (similar ones occur in Brittany) and dimpled the hillsides in west Somerset[387]—a nivation hollow at the Slipper Stones, south of Okehampton, may imply a local snowline at 550 m.[388] Freezing, thawing and softening of the underlying clays, to a depth of 30–60 m, caused mass-movements,[389] e.g. in the Weald Clay, in Chalk, in Berkshire, and in Northamptonshire and Yorkshire (Barnsley) similar to those which are known from central Europe,[390] e.g. Bohemia.

Frost and melting snows caused the soils to creep over the barren and frozen slopes, e.g. the "head" and coombe-rock (see below) and the rubble of the Cotswolds Hills.[391] They created fans of *tjaele* gravels in embayments in the escarpment north of these hills which merge into stratified fan-deltas and terraces on the lower ground.[392] They initiated floods at lower levels and distributed torrent-bedded sands and gravels as about Canterbury.[393] Britain's mean annual temperature may have been about 0°C[394] and the winter temperature in southern England *c.* 11°C lower than now.[395]

The country was a tundra and many species, now of restricted range, were then widespread: their distribution was contracted and broken up post-glacially as the result of the growth of dense forests and of peat moors above the forests and the disappearance of suitable soils.[396] Some of the species even became extinct, e.g. *Betula nana* and *Naias marina*. H. Godwin (1953) has recently given a list of the plants now known from the pleniglacial and lateglacial times in Britain.

Trail, head and coombe rock. Solifluxion has been well studied in southern England where it constitutes the "trail", "head" and coombe-

rock—earlier names[397] were "rubble drift", "angular detritus" and "erratic warp". A historical retrospect has recently been published.[398] The trail of O. Fisher,[399] an irregular superficial stony loam of local material, up to 5 ft (1·5 m) thick, has an uneven base, often festooned and contorted, and pebbles which have been turned vertically by repeated freezing and thawing. It is very extensive and not uncommonly in the Thames basin merges into the Flood Plain Terrace (see p. 1000).

The head, which H. B. De la Beche[400] early described, is an accumulation of local rocks, sharp and angular, which is coarse close to the hills but farther away becomes smaller and mixed with fine material. It spreads irregularly over low ground, sheeting the sides and floors of valleys,[401] as in Pembroke and Cornwall, the Channel Islands and Scilly Isles, (at Sangatte and in Brittany), and in the West Midlands and those parts of west Yorkshire, e.g. lower Wharfedale and lower Airedale, which were ice-free during the later stages. Its subaerial origin under cold, solifluxion conditions was early recognised[402] and is proved by the angularity of its constituents and by distortions in the underlying strata.[403] Its glacial age is demonstrated by its passage on to the infraglacial raised-beach platform and accompanying blown sand, and by its association with loess,[404] with cold mammalia,[405] e.g. mammoth, woolly rhinoceros and reindeer, and with an arctic flora as at Ballybetagh Bog, Co. Dublin,[406] and at Bovey Tracey.[407] The angular debris of the cave-earth and bone-fissures may be its equivalent. Head probably originated during each major increase in the glacial cold—two horizons are known from Cornwall—though the state of cementation, controlled by the local drainage and the composition of the materials, may not be an accurate guide as to its age.[408] Nevertheless, it forms a valuable clue to the elucidation of English Pleistocene chronology: dissected "heads" are largely restricted to the south of England while the newer head occurs much farther north and overlies and frequently incorporates deposits of earlier ice-sheets.

The coombe-rock,[409] a term G. A. Mantell[410] first introduced geologically, is a structureless mass of unrolled and unweathered flints, embedded in a matrix of chalky paste and disintegrated chalk. Its narrow tongues run into the valleys or "coombes" of Sussex and often pass into brickearth. With a thickness of 50 ft (15 m) or, as near Brighton, of 80 ft (*c.* 25 m), it lies at various heights in positions unrelated to any present river-system. It mantles the major outcrop of the chalk north-west of London, e.g. near Aylesbury, and spreads widely over the North Downs and through Kent and Sussex, as beneath Chichester and Selsey where it forms clean brickearths, and originally extended beyond the coast near Brighton and Worthing.

The coombe-rock (erroneously credited to pluvial, marine or subterranean erosion[411]) is the solifluxion facies of chalk areas[412]: its structure is frequently contorted and its flints are often vertical. It was formed by sheet-flowing or sludge-creep, not only in the coombes but over the whole of the dip slopes, aided by wind when the ground was frozen and unprotected by vegetation. The ground becomes impenetrable to-day during hard frosts[413] and is upheaved by *c.* 3·8 cm, the frost penetrating *c.* 30 cm.[414] The associated land-shells and mammals, e.g. mammoth, woolly rhinoceros, reindeer and musk ox, show that the climate was cold. Its age is fixed[415] by the raised beach upon which it lies, as at Brighton and Sangatte, and by the river-terraces. In the Thames valley,[416] it contains mammoth and woolly

rhinoceros, rests upon the Northfleet Mousterian floor, and near Grays has the gravels of the Flood Plain Terrace banked against it. It overlies or embodies Mousterian (Levallois I–II) implements,[417] as at Baker's Hole and Sangatte, together with derived Abbevillean or Acheulian and remains of the *faune chaude*.

The coarse stanniferous gravels of Cornwall,[418] which enclose stones of torrential nature, are synchronous with the head and of similar origin. Waters from melting snows eroded the valleys so that small tributaries hang as above the Dart.[419] Frost liberated the tin-ore at higher levels: iron pyrites and soluble copper ores point to the absence of chemical weathering.[420]

Clay-with-flints. The clay-with-flints of W. Whitaker[421] is a comprehensive but ill-defined category of miscellaneous materials in which the proportions of clay, sand and flint vary greatly. "Foreigners" as a rule are lacking and the bedding is obscure. Bounded below by an uneven surface, it changes rapidly in thickness, frequently filling basin-like hollows and funnel-shaped "pipes" of considerable depth. It covers much of the interstream tracts in south England from Sussex to Hertford and Devon, and spreads over the Downs of north Kent and the Isle of Wight, its boundaries being indefinite on both Chalk and Tertiary outcrops.

In age and origin, the deposit is probably composite,[422] more than one process having acted on many kinds of strata. It represents the insoluble residue of the Chalk, reinforced with Tertiary waste which added quartz pebbles and rounded flints. On the 400-ft (120 m) platform it may be Pliocene—it passes under the till in the London District north of the Thames—but is no doubt younger on the lower ridges. Floods from melting snows and solifluxion distributed and redistributed it during the Glacial period; in many places, as in Kent, it encloses palaeoliths.[423]

Plateau gravel. The clay-with-flint may be the equivalent of the more pebbly Plateau Gravel ("southern drift",[424] "hill gravel"[425]) which, up to 20 ft (6 m) thick, caps innumerable isolated hills or spreads across plateaux and watersheds,[426] as around London (Norwood, Esher, Crystal Palace, Bagshot Heath), on the North Downs, in New Forest and the Isle of Wight, and about Marlborough and Oxford. Less clean and rounded than river-gravels and more decalcified and current-bedded, the gravels consist of pebbles of chalk, flint and Tertiary material, e.g. quartz and grey-wethers, with Lower Greensand chert, Bunter quartzite and igneous rocks. In the Oxford district the constituents are chert from Yorkshire and Lincolnshire, Hertfordshire puddingstone, black flint from the Chiltern Hills, Carboniferous crinoidal limestone, tourmalinised slate, elvan and rhyolite from Cornwall and Devon and akerite from Norway.

Formerly regarded as marine,[427] the gravels are now considered to be fluviatile relics of old floors or alluvial plains.[428] Their age is somewhat uncertain; for altitude is a doubtful criterion and the difficulty of distinguishing plateau gravels from terrace gravels or Tertiary deposits is a commonplace in English geological literature. That their antiquity is considerable is proved by their condition and their independence of the present drainage, though they are related to the valleys in the Salisbury and Avon districts and descend towards the Thames valley, thus indicating that the main drainage already existed.[429] They probably represent several stages of denudation at present undifferentiated, some Pliocene, some Pleistocene (they contain

palaeoliths[430]) when they were modified[431] by floods from melting snows, by creep and rainwash, and by solifluxion which arranged the pebbles vertically and contorted the upper layers and even those of the subjacent clays, such as the Wealden Clays of the Isle of Wight. On the northern edge of their distribution, they may contain outwash material, as in Hertfordshire,[432] or pebbles that have retained their ice-scratches, as near Oxford and in Cambridgeshire.[433]

Solifluxion, under one or other designation, was therefore widespread in southern England. It rounded the outlines,[434] contorted the surface-layers (see above), curled up hibernating lemmings,[435] deposited materials resembling boulder-clay[436] in Kent and Sussex, and, helped by frost-upheaval and gravitation settling, transported boulders like those now radially dispersed about the Cornish Crags.[437] With melt-waters, it produced the vast spreads of local, often angular detritus which skirts the foot of the Cotswold Hills and Malvern Hills and grades into the Main Terrace of the Severn[438] (see p. 1005). Like the gravels on the south coast they imply swifter streams than those of the present day.

Solifluxion features, just mentioned, circumboreal species in the present flora of Normandy[439] and mountain species in south Europe and northern England and the Scottish Highlands suggest a cold climate for north France.[440] Slope deposits, blockfields, asymmetrical valleys and other periglacial effects are confirmative.[441]

Date of tundra. The date of the glacial tundra has been much debated. Each glaciation presumably had a faunal and floral migration[442] and a periglacial tundra,[443] though the nature and width of the tundra doubtless varied from glaciation to glaciation—the earlier tundra periods in Europe had North American species[444] and while they had *Betula nana* and a few mosses they generally lacked cold plants including *Dryas octopetala*.[445] The earlier glaciations had very little effect upon the mammalia which only assumed their arctic aspect during the last or last two glaciations (see p. 913) as evinced by their range in Europe (see p. 1031)—earlier glaciations may have induced changes which only later came to fullest fruition.[446] The tundras may therefore with more likelihood be referred to the last two glaciations[447] which had virtually the same fauna, though each had its peculiar types: the two reindeer horizons in Castillo have been assigned to them.[448] The arctic flora at Deuben and Przemysl (200–220 m) and at Oeynhausen has been put in the penultimate glaciation[449], as have the windworn pebbles (*Windkeien*) of various parts of the Netherlands[450]; and the polygonal ground at Niederlausitz is referred to the Warthe glaciation.[451] Solifluxion features belonging to two glaciations have been described from Westphalia[452] and Magdeburg,[453] and frost-wedges from Dillingen on the Danube have been given the same ages.[454] Similar wedges belonged to the Saale glaciation near Leipzig[455] as did the *Brodelboden* in Upper Silesia.[456] Nevertheless, Günz ice-wedges have been claimed for the Lower Rhine[457] and lower Pleistocene cryoturbation from France and the Low Countries (see p. 937); central Bohemia was in the periglacial zone during each of the older glaciations.[458]

The advance of the northern oreophytes in the Pyrenees, Sierra Nevadas and Great Atlas took place during the Riss and Würm glaciations.[459] The tundra in Holland belonged to the last glaciation: the earlier periods, it is said, had forests about them.[460] The floral and faunal exchange attributed

to the last glaciation, has by some been referred to the penultimate glaciation[461]: the corridor was then narrower and the climate severer (cf. p. 1031) and the maximum cryoturbation occurred then in the Paris basin.[462]

Be all this as it may, the tundra period par excellence was the last glaciation,[463] including its later phases, when Europe had its longest and severest cold (see p. 1031) and the tundra its greatest width. Its lateness is demonstrated in various ways: the arctic layers are related to the valley floors and low river-terraces, as in the Thames and Cam (see pp. 1001, 1004), and contain remains of mammoth, as at Borna,[464] and of mammoth, woolly rhinoceros and musk ox near Kattowitz in Upper Silesia[465]; the "trail" fauna is cold[466]; the *Dryas* clays interdigitate with ground-moraine near Lübeck and on the Kiel Canal[467] and with Yoldia Clays near the boundary of the lateglacial sea.[468] In the Alpine region,[469] alpine-arctic species, e.g. *Betula nana*, *Salix herbacea*, *S. myrtilloides*, *S. polaris*, *S. reticulata*, *Dryas octapetala*, occur in a few localities, all lateglacial in age though *Betula nana* and certain arctic mosses are known from earlier Pleistocene horizons. The isostatic uplift had reached an advanced stage, amounting to two-thirds of the total, in Estonia and Gotland while *Dryas* still tarried there; and solifluxion and other cryoturbate features are mostly of this date[470]—H. Quiring,[471] by relating them to the Main Terrace of the Rhine and Younger Loess, obtained an Elster age—being generally absent from this latest drift.[472] In Holland, the tundra period has been subdivided into two, Würm 1 and 2[473] or into three stages (Florschütz, 1953). A fossil solifluxion head recently reported from coastal Portugal is later than the Tyrrhenian shore-line (Guilcher, 1949). The *hochglazial* has been designated full-glacial (Godwin, 1953) or pleniglacial (Hammen, 1951).

During the lateglacial phase in Europe, the growth of moor and of limnic sediments was extremely scanty[474]: at higher levels, growth was prevented by cold, at lower levels by dryness. The absence of woods is proved by the high NAP values (see p. 1444) which may be as high as 666% or even 4100%.[475] The pleniglacial landscape was a treeless tundra, the lateglacial one treeless or a lightly wooded park-tundra; in Great Britain, open habitats and fresh soils abounded and had a herbaceous flora rich in species of the categories of ruderals and weeds and aquatic and marsh plants.

In North America arctic conditions, it has been suggested, persisted about the ice into late stages: low intersecting ridges, 1–3 m wide and 23–150 m long, accompanied by involutions, wedge structures and polygonal ground, form a fracture pattern on the flat muds of Lake Agassiz of late-Wisconsin age.[476]

(c) *The Origin of Arctic Life*

Centres of evolution. The question of the origin and evolution of the arctic fauna has been attacked by some zoogeographers; but a comprehensive treatment from a modern viewpoint has only recently been attempted.[477]

It has usually been assumed with E. Forbes, C. Darwin and J. D. Hooker that the arctic fauna and flora of Eurasia and North America lived in circumpolar lands and were compelled by the glacial cold and ice-sheets to seek as *émigrés* a home in more southerly latitudes.[478] This assumption, frequently made for example for the mammoth, woolly rhinoceros, musk ox, arctic hare and the "Siberian fauna" generally, and for their invertebrates, e.g. the

Turbellaria,[479] fleas[480] and birds,[481] postulates a polar climate preglacially.[482] It is somewhat justified by the tempo of evolution, the widespread distribution of arctic life, which may have originated in Pliocene time, and by the differentiation of the alpine and arctic life, the latter taxonomically most heterogeneous and including in all its faunal classes generalised or primitive groups alongside specialised ones.

The sole divergence of view concerns the actual centre of differentiation. While some, supporting themselves on Petermann's hypothesis of an arctic polar continent, accepted the north as the original home of arctic life,[483] others thought this life originated as a mountain biota in the Altai,[484] north Asia[485] (arctic birds, for example, evolved in eastern Siberia and about Bering Sea[486]) or the Alps,[487] or as an arctic biota in Scandinavia,[488] Greenland[489] or North America[490] (including the Bering Sea region), or in multiple regions of parallel evolution and exchange[491]—the reindeer, for instance, originated in Europe,[492] Asia[493] or North America.[494] Certain forms, such as *Arenaria ciliata*, *Primula farinosa* and *Poa flexuosa* which were apparently indigenous in the mountains of central Europe, spread northwards into boreal regions and became differentiated into subspecies.[495]

The Antarctic witnessed parallel events;[496] its life evolved possibly from W. Gothan's "Antarcto-Tertiary Flora" (see p. 695).

It is likewise stated that the alpine flora, including Edelweiss (*Leontopodium alpinum*) and first distinguished by K. Gesner in 1555, inhabited the Eurasian mountains in Tertiary time[497] as Engler's "Arcto-Tertiary flora".[498] It had evolved from the plain flora during the middle of the era in the temperate latitudes of the northern hemisphere where it is now represented in the floras of south Japan, central China and south-east U.S.A. and gave off, possibly as polytrope forms in several separate regions (such as the Alps, Pyrenees, Carpathians and Asian mountains), a disjunct mountain flora, the oreophytes of Diels.[499] Its preglacial origin has been frequently asserted for the Alps[500] and adjacent territories (Corsica, the south Balkans and the Sierra Nevadas have alpine species without a single arctic plant[501]) while, as just observed, others regard the fauna and flora of northern Asia or southern Asia as ancestral to the alpine biota.[502] The recent mountain coleopteran fauna, e.g. of the Carpathians, is also in its essential features of preglacial age[503]: it was completely exterminated in northern Europe, was decimated in central Europe, e.g. in the Variscan horsts, and survived only in south Europe in approximately its original condition.

On the other hand, it is argued that polar regions are the graves of life which steadily ebbs polewards and are unsuited as creative hearths.[504] Their inhabitants, e.g. reindeer and glutton, are modified descendants of southern ancestors which have sought the colder climate not from preference but because they have been driven into it by stronger forms[505]—the butterflies of the Arctic represent types that elsewhere characterise rough and forbidding country, waste lands, or more or less arid regions.[506] Structure and habits have been adapted to the rigorous climate.[507] Some subpolar species, for instance, exhibit closer relationships to their congeners occupying adjacent territory in temperate lands than to corresponding polar forms dwelling elsewhere in the Arctic.[508] The early Pleistocene microtine fauna may have spread in Europe from the south.[509]

The birthplace of any floral element may be sought on systematic grounds or by examining modern distributions. These methods are always difficult

to apply and in this particular case are unusually so. The origin of the arctic life is shrouded in darkness. Nothing is known of the late-Tertiary flora of the Alps or Carpathians[510] or of a tundra flora and fauna in preglacial Asia.[511] The history of the majority of arctic animals is also unknown.

The bipolarity of land plants and animals,[512] that is the occurrence of identical species in boreal and austral zones that are absent from tropical latitudes, has been variously explained: by independent creation[513] or independent evolution,[514] e.g. by descent from tropical forms originally cosmopolitan and distributed through all latitudes[515]; by migration from the tropics[516]; by transequatorial migration,[517] on the monoboreal hypothesis, from the Antarctic[518] or from the Arctic across Africa (from peak to peak[519] or by continuous migration over plains at the mountain foot[520]), or through the Malayan-Papuan[521] region, along the Andes in preglacial[522] or Quaternary times,[523] or along the Dolphin Rise in early Pleistocene times.[524]

The connexions in austral regions, e.g. between South America and Australasia, may have been made by one or more of these transequatorial routes associated with a transantarctic migration[525] by accidental dispersal, by migration over land-bridges, or by continental displacement.

Tertiary polar climates. The problem is closely bound up with that of the Tertiary climates in high latitudes. While a Tertiary zonation of climate has been denied[526] it is certain that climatic zones existed during that era but were broader and less sharply differentiated: the mountains also had altitudinal zones with distinctive life belts. Throughout geological time, the world's climate, to judge from both geological and palaeontological evidence, has generally been genial and mild (*akyrogenic*; *pliotherm*) with ungenial and glacial (*kyrogenic*; *miotherm*) interludes; the latter have probably occupied less than one per cent of geological time[527] (upper Pre-Cambrian, lower Cambrian and Permo-Carboniferous) and recurred perhaps with a periodicity of about 250 million years[528] (due possibly to a corresponding periodicity in the fluctuations of solar radiation). The world's temperature, except probably in the tropics, was higher and its climatic zoning much feebler. Accordingly, the normal climate of the planet has been unlike the present which is most certainly abnormal,[529] if not geo-catastrophic.[530]

The present physical, geochemical and geological processes (partly because of man's activities) differ in some degree and in intensity from those of most of geological time; the continents and mountain ranges are more elevated and extensive; the energy of rivers, both above and below ground, is unusually high; readily eroded drifts swathe widespread areas; and the present ice-masses, a legacy of the Glacial period, sharpen the climatic contrasts. The present does not reflect the climatic periods of the past any more than it does the epeirogenetic or orogenetic periods[531] (see ch. XXIX). The rapid fall of temperature through the latitudes causes numerous changes,[532] namely, east winds to blow in arctic regions instead of the west winds of the normal geological past, a decrease of storminess in higher latitudes, the formation of the Aleutian and Icelandic "lows" and of the polar fronts and storminess in middle latitudes in place of steady southerly winds. It sharply limits the subtropical high-pressure belts on the poleward sides and enhances the subtropical high pressure belts and the equatorial troughs of low pressure. It also cools the great body of sea-water[533] and especially the seas off the western coasts of the continents by the uprise of the cold bottom waters.[534]

During the Tertiary, higher latitudes had an equable climate, with smaller

temperature oscillations and warmer winters; they were devoid of ice-caps (cf. p. 596) or frozen seas (see below) and in Alaska at least of frozen ground,[535] as the great depth of the weathered zone, including auriferous gravels, indicates. Glaciers may, however, have existed preglacially on the highest mountains of the Arctic, including Alaska. The evolution of the forest or taiga birds in north-east Siberia and Alaska, as well as the palaeobotanical evidence, suggest a temperate climate both in north-east Asia throughout the Tertiary era[536] (in accordance with the taiga itself which evolved in Tertiary time[537] in a warm climate) and in south and east Siberia and a Bering centre which included north-west North America—the taiga birds, which in east Siberia include endemic forms, diminish westwards from here into Europe where they were preglacial. This refrigeration may have caused the evolution of the herbaceous flowering plants from arborescent ancestors,[538] the former being better protected from the cold by their short life-cycle and the greater ease with which they find protection under the snow.

The fossil floras of the Arctic betray no sign of dwarfing in leaves or stems. The plants as a whole were of the temperate type, though it is possible that those from Tertiary Greenland and other arctic islands belonged to the foothills and plains, and that the alpine flora of the high ground has not come down to us.[539] Iceland's flora before the Ice Age was almost of the same type as that of warm, temperate areas to-day.[540] Birches in Grinnell Land and Spitsbergen were far taller and bore much larger leaves than those of their stunted successors in more southern arctic countries to-day.[541] The fossils in the Nome gravels of Alaska denote a climatic shift compared with the present of 1200 miles (*c.* 1900 km).[542] Elm grew in preglacial Siberia[543] when during the Pliocene, *Brasenia purpurea* lived in the basin of the Ob[544] and conifers (*Pinus monticola* and *Picea wollosowiczi*) grew in the Omoloi River and *Juglans cinerea fossilis* and *Picea wollosowiczi* in the Alden River.[545] In the Villafranchian of Shansi, Shensi and Kansu red concretionary clays developed on the slopes and *Lamprotula* swarmed in the rivers.[546] Beech, hornbeam, walnut and holly occurred in the oldest Pleistocene of North Siberia[547] (Tobolsk)—the date may be considerably earlier[548]—and other temperate forms, including North American plants, inhabited eastern Siberia.[549] The plants under the fossil ice of Siberia (see p. 649) are closely related to those in present-day California and Japan.[550] The exchange of plants between Asia and North America and the spread of the horse and camel-llama from North America to Asia about the Plio-Pleistocene transition indicate a warm and possibly drier climate about the Bering Sea at that time.[551]

Siberia's Pliocene freshwater fauna included numerous unios and fish genera now absent from that region.[552] The few relics of its preglacial life include no arctic species. On the contrary, a Hipparion fauna lived in south-west Siberia,[553] and the remains of warm mammals, e.g. *Diceros merckii* and *Elasmotherium sibericum*, have been found in river-terraces in the Lena and Yenisei.[554] Even at the end of the Pliocene the climate of the plains of Russia and west Siberia was warmer and more humid than that of modern times.[555] The arctic life, therefore, which is younger than the arcto-Tertiary flora, is at earliest Pliocene; the tundra may be Quaternary.[556]

Glacial conditions in the Antarctic appear to have been the exception and not the rule[557]: no clear indication of a former Ice Age is apparent in any formation so far examined. In Mesozoic and early Tertiary times temperate

floras at least grew in the Antarctic, and some of the southern genera of conifers may even have originated on a trans-antarctic bridge between South America and Indo-Australalasia.[558]

Influence of Glacial period. The Chinese-American element (see p. 691) was probably derived from a circumpolar source and driven southwards by the ever-increasing cold of the Pliocene. The alpines also evolved in late-Tertiary time, as is generally thought (J. Briquet, R. Chodat, H. Christ, O. Heer, M. C. Jerosch, F. Kerner, A. Pokorny, A. Schulz, C. H. Vogler) in the Alps or independently in other mountains,[559] including the Altai, alternatively as a plain flora in arctic regions.[560]

Many groups, including the insects and molluscs, persisted almost unmodified throughout the Pleistocene.[561] Marine forms in particular naturally suffered little extinction; in the Coralline Crag of East Anglia 38–40% of the forms are extinct,[562] in the Calabrian 11%,[563] and in the basal Pleistocene of Java 20%.[564] Yet the Ice Age, with its climatic stress and vicissitudes and varying physiographic and edaphic conditions, intensified the severity of selection and furthered advances in organisation—exposure to very low temperatures enhanced the mutability of forms.[565] By its alternate contraction and expansion of occupation areas, mutation and re-combination processes were given the run of natural experimental fields on an enormous scale.[566] The Ice Age introduced biological changes in the annual life-cycle and caused the loss of bisexual reproduction in some forms; affected profoundly the habitat, nutrition, reproduction, mode of life and morphology of certain groups[567]; evolved several arctic and alpine species,[568] including many herbaceous types, especially those with well-marked methods of perennation; changed the role of the alpine flora in the mountains of central Europe from a subordinate to a dominant one[569]; produced local genera, species, varieties and races,[570] e.g. of *Daphnia* and *Bosmina*, for under migration there has been selection and extinction; encouraged the survival of tetraploids and promoted the formation of tetraploid species[571] (which are able to occupy more rigorous and exacting habitats) and of fertile hybrids where (as is illustrated by plants, molluscs, beetles, fish and birds) species were isolated during glacial time and in expanding postglacially have overlapped their regions, e.g. the tetraploid species of *Paeonia* in the Mediterranean and Caucasus where migration led to isolation.[572] Similar hybridisation probably resulted from previous glaciations (see p. 906) and occurred in North America,[573] e.g. in south-eastern United States and in the Mackenzie district of Canada. The great preponderance of polyploids in glaciated regions is probably chiefly the result of hybridisation and chromosome doubling of species which came together after long periods of isolation in glacial refugia, and the selection of favourable gene combinations among the newly established polyploids. The Ice Age also directly stimulated the evolution of the present stenothermal species[574] and the arctic and alpine flora and fauna,[575] including the glutton (see p. 806), musk ox,[576] and arctic fox[577] which then developed their morphological characters and climatic adaptation to cold conditions. The reindeer may also have descended from an early Pleistocene temperate form[578]—its adaptation has been placed in the last glaciation[579]—though W. Soergel[580] thought its adaptation, like that of the musk ox, glutton, arctic hare and other arctic forms, to a cold climate was complete by the early Pleistocene. The rarity or absence of cold mammalia in early Pleistocene is explained by the fewness of caves or of loess horizons of that

age. Yet reindeer occurred at Süssenborn, Mosbach and Frankenhausen (= pre-Mindel), musk ox in Swabia (= Mindel), glutton at Mosbach, Cromer and Püspökfürdő (= pre-Mindel). The lemmings like the reindeer may have become acclimatised to the glacial vegetation,[581] though the strong specialisation of the skeleton and certain related Pliocene forms may point to its specific isolation at an earlier date.[582] The ancestors of the lemmings lived at Oberpfalz in lower Pleistocene time with animals of a mild climate and even *Lemmus* and *Microtus*, to judge from pre-Pleistocene remains, may have been temperate animals.[583] Numerous freshwater pulmonates in North America may have evolved during the Pleistocene,[584] and *Planaria alpina* may have been modified into a cold species[585] though A. Thienemann regarded it as a preglacial form. E. Hultén[586] has suggested that the hardiest of the boreal plants developed into the arctic species north of the ice-sheets and that the boreal plants south of the ice evolved into the arctic-montane plants. The freshwater plankton, in Europe at least, may also be connected with the Ice Age.[587]

The glacial cold and white snow may have been responsible for the white coloration of polar animals and birds,[588] e.g. ptarmigan, snowy owl, snow bunting, arctic fox, arctic hare, polar bear, white walrus, lemmings, stoat and ermine, partly as a means of heat conservation or as a concealing coloration—ptarmigan, for instance, keep to snowy patches in spring until their white winter plumage is lost.

This inheritance by the Glacial period of a fauna and flora undifferentiated into arctic and alpine elements that evolved in its rigorous climate[589] may perhaps be justified by the evidence just outlined, as well as by the fact that, contrary to earlier opinion, certain members of the arctic fauna, such as the mammoth, woolly rhinoceros and cave bear, evolved from warmer species on the plains of central Europe[590] (see ch. XXXIV), north Siberia[591] or eastern Asia.[592] The late appearance of the arctic element in the glacial succession (fig. 157, p. 818) is confirmation. The whole assemblage of species now living on the northern continents (and in the northern oceans) may be of Pleistocene origin, for cold-water stenothermal plants and animals can only have arisen under a climate at least as glacial as that of to-day.[593] If evolution is in any respect due to changes in the conditions of life, then during the Glacial period, if ever, great alterations should have taken place. The mammalia of Europe have in fact all changed their specific characters since the Villafranchian.[594] Man's evolution and dominance were facilitated by climatic change[595] (cf. p. 864).

2. On Sea

(*a*) *Chilling of the Sea*

The effect of the Ice Age upon marine life was little less than that on land life. Warm forms lived during the early Tertiary[596] in the North Altantic and North Pacific. In late-Tertiary time, the Arctic Ocean seems to have been open and free from ice since several species,[597] common to the two oceans—the amphiboreal element of L. S. Berg[598]—have been found in the North Atlantic and North Pacific, namely, forms either still living, including fish, crustacea, molluscs, hydroids and sea-urchins, or living on one side only and of Pliocene age on the other, e.g. *Liomesus canaliculatus* (Bering Sea, Iceland, New England) and *Neptunea castanea*, *Sipho herendeeni*, *Trichotropis*

insignis, *Serripes laperoussii* and *Littorina palliata*, all of which occurred in Bering Sea and New England. This striking discontinuity in a number of groups witnesses to an earlier continuity and a free faunal exchange. It agrees with the occurrence of molluscs and other forms, characteristic of a mild climate, in Pliocene beds at Nome, Alaska,[599] where the climate is now fully arctic. The present discontinuity of the amphiboreal element is a result of glacial conditions.

In the Arctic, the ice probably accumulated on the land before the pack-ice began to cover the polar basin[600]; for the first meteorological effect of glaciated mountains near the sea would be to increase the local storminess and diminish the chance of freezing until at last sufficient surface fresh melt-water was produced. When once, however, the temperature at the pole fell to *c.* $-17 \cdot 5$°C the lowering of the winter temperature amounted to *c.* $7 \cdot 2$°C.[601]

The ice obliterated all life from Europe's epicontinental seas it overrode, e.g. the North Sea, and by lowering the level of the world's oceans increased their salinity and not inconsiderably affected shallow-water species which were sensitive to the muddying of coastal waters.[602] Not only was the polar ice on a bigger scale,[603] filling the Arctic Ocean, the Bering Sea, the Greenland and Labrador seas and reaching into the North Atlantic beyond the southern coasts of Greenland and Iceland, but the seas around the ice-sheets in more southerly climes became glacial—J. Esmark[604] deduced an *iishav* for Norway. The proximity of land-ice, drift-floes and bergs (cf. their influence in modern seas and fjords[605]), ice-winds and melt-waters (cf. recent investigations in the North Atlantic[606])—the cold freshwaters rested as a skin on the saline waters below—and the drift of snow from the lands, as off North-East Land to-day[607]—all these factors helped to cool the adjacent seas. The lowering of sea-level which reduced the depths over the submarine ridges, e.g. the Wyville-Thomson Ridge, also helped to cool the seas by shutting out the warmer waters.[608]

This chilling, which with the ice-sheets drove the algae and the strand halophytes southwards,[609] was felt in East Anglia (*Leda myalis* Bed, see p. 995), on the south coast of England with its *Balaenoptera borealis*, the Asturian coast—*Pecten* (*Chlamys*) *islandicus* and *Cyprina islandica* occur in caves on either side of the Pyrenees[610]—in the Dordogne and Gironde where remains of *Phoca groenlandica*, found to-day off Novaya Zemlya, Iceland, Spitsbergen and in the Kara Sea, have been obtained[611] and Magdalenian man in south France made drawings of this creature and of *P. foetida*.[612]. It was experienced as far away as Senegal and Morocco[613] where the Sicilian contains *Acanthina crassilabrium* and molluscs occurred whose present normal habitat is north of St. Vincent, and in the Mediterranean: in Calabrian and Sicilian times several upper Pliocene species were banished to the west African coast and the *immigrés du Nord*,[614] noticed by R. A. Philippi in 1836, were introduced. These included foraminifera[615] and *Pecten* (*Chlamys*) *islandicus*, *P. tigrinis*, *Mya truncata*, *Trichotropis borealis*, *Buccinum groenlandicum* (present range: Bay of Biscay–Spitsbergen), *Cyprina islandica* (present range: Bay of Biscay–White Sea) and *Panopaea norvegica* (present range: Kattegat–White Sea), all of which have now vanished from the Mediterranean. They chiefly inhabited the northern part of this sea. It has been said[616] that the shells do not prove a colder Mediterranean, since they are climatically indifferent and the Pleistocene shells show no sign of cooling—*Cyprina islandica* is found as far south as Arcachon ($44\frac{1}{2}$° N. Lat.) and overlaps with

certain southern species such as *Astralium rugosum*. J. G. Jeffreys considered the Sicilian fossil a distinct sub-species. Nevertheless, it seems necessary to accept the old belief,[617] restated by M. Gignoux,[618] that the waters were cooled, in both the Calabrian and the Sicilian; the northern part of this sea was as cold as the North Sea on the outer coast of south Norway—the 7°C isotherm which leaves the land in Bergen was displaced to Porto and passed over the Gulf of Genoa, crossing the Adriatic south of Pola and the north coast of the Aegean; the January isotherm was probably under 0°C[619] (cf. pp. 655, 1072). *Pecten islandicus* at present reaches no farther south than the west coast of Sweden. Foraminifera, now restricted to very cool-temperate or subarctic seas, have been obtained from cores at the bottom of the Tyrrhenian Sea.[620] Varying sea-levels may also have introduced changes of this kind; thus physical events, by submerging the Wyville-Thomson Ridge or widening and deepening the channel at Gibraltar, would have allowed lower and colder layers from the Atlantic to enter[621] (see p. 1271). The temperature, however, was not cold enough for coastal ice since *galets exotiques* like those of the English Channel (see below) are unknown in the Mediterranean.[622]

On the opposite side of the Atlantic, during one glacial epoch at least, arctic shells with ice-rafted boulders found their way to the coast north of Boston.[623] *Neptunea stonei*, a species of northern affinities, has been found in deposits of Wisconsin (?) age as far south as North Carolina,[624] and walrus wandered as far south as Virginia and South Carolina[625] (Charleston). Cores in the sea-floor at a depth of *c.* 1000 fathoms east of Atlantic City reveal the former existence of foraminifera, including *Globigerina pachyderma*, which are now mostly found within the Arctic Circle[626]: the fact that all the species of the arctic microfauna are still living indicates that the deposits are fairly recent. Arctic foraminifera, e.g. *Cassidulina laevigata*, *C. subglobosa* and *Globigerina bulloides*, occur in other North Atlantic bores.[627] Colder air from the north may have exterminated the tropical life in the Bermudas and the corals in their shallow seas.[628]

Cores reveal that the Arabian Sea and Atlantic Ocean were slightly colder[629] (see p. 921), e.g. off the east coast of America, in the Caribbean Sea and off the Irish Coast, while the disappearance of warm forms from the north coast of Chile[630] (27·30° S.) and the occurrence of boreal foraminifera (e.g. *Cassidulina* and *Polystomella*) in the Manzaki Beds of Japan and the Santa Barbara and Lower San Pedro Beds of California,[631] and the relict fish fauna in the Gulf of California and its streams,[632] register a contemporaneous cooling of as much as 10°C in the Pacific. The pilot whale occurred at Colombo[633] in the Indian Ocean. Nevertheless, the persistence in the northern part of the Pacific Ocean of many species or groups of species of various genera, no longer represented in the North Atlantic marine fauna, suggests that its cooling was not serious.[634] This agrees with the survival of the Tertiary flora in Japan and Amur region, with the smaller extent of the ice-masses about the North Pacific and of floating ice in the ocean itself, and with the displacement of the marine shells through only 4° of latitude in the Japanese seas.[635] Orogenic movements (see ch. XXIX), however, seriously complicate correlations with events in other oceans.

The Southern Ocean and its offshoots along the west coasts of the southern continents, e.g. South America, were likewise cooler, owing partly to the greater uprise of bottom waters.[636] The Antarctic Convergence[637] (see

below), with which the line between the diatom and globigerina muds is closely connected, was thrust northwards, and floating ice scattered materials beyond the present limits of drift. J. G. Andersson found cold Bryozoa in Quaternary deposits on Cockburn Island, and the *Meteor* Expedition discovered a foraminiferal stratification in the equatorial Atlantic (see p. 921). A similar stratification was found in the Southern Ocean and the southern part of the Indian Ocean.[638] The appearance of a number of molluscan species with subantarctic affinities, notably *Chlamys delicatula* and *Tawera subsulcata*, in the Nukumarian beds proves the existence of colder waters in New Zealand (Fleming, 1944, 1953).

The cold shells of the periglacial zone, far removed from the coasts, are now inaccessible, though very occasionally, as in eastern North America, storms have swept them on to modern beaches.[639]

These cold oceans, by their greater absorptive capacity, have withdrawn a small percentage of the oxygen and a much higher percentage of the carbon di-oxide from the atmosphere,[640] with reactions upon weathering and land-life which have yet to be traced. The lower temperature diminished the degree of saturation of the water with calcium carbonate, particularly of the sub-surface layer. A downward diminution of the calcium carbonate content of the sediments has been recorded in the Globigerina oozes flooring the Atlantic.[641]

An epoch when all the oceans were cooler seems to be implied by the fact that three types of cool or cold water deposits, namely, glacial marine deposits, red clay and sediments with cold water foraminifera, formerly had a greater area and are now buried under a comparable thickness of foraminiferal ooze or limey blue mud (see p. 921).

Marginal coral seas. The glacial chill, which probably shifted the Convergences (see below), was greatly damped in tropical seas, whose marine life, for example, off Peru, the Philippine Islands and the West Indies, suffered no appreciable change.[642] Whether it extended into tropical seas, as suggested,[643] is indeed doubtful, though the greater development of siliceous organisms in the Guinea Basin and Cape Verde Basin prove cold waters here[644] and that the Atlantic bottom water extended much farther than now (see p. 921). Nevertheless, the stirring of the immense sediments and the subaerial and marine erosion that accompanied the universal sinking of sea-level (see p. 1355) and the world-wide migrations of the zone of breakers killed off the corals throughout the coral seas during each glacial epoch, though the interglacial growth was vigorous.

This "glacial control" theory of coral reefs, suggested by A. Tyler[645] and Penck,[646] was elaborated by Daly.[647] The corals, it is supposed, grew post-glacially on platforms abraded long preglacially as well as by the waves of the lowered glacial ocean, as is testified by the uniform depth of the submerged platforms within the atolls (*c.* 45 fathoms; *c.* 82 m), of the drowned and alluvially filled valleys, and of the beaches around the bigger islands. This glacial control theory which explains satisfactorily the extreme scarcity of atoll and barrier lagoons greater than 80–90 m in depth, the relatively small and uniform volume of the encircling reefs, and the lesser depths of small lagoons, has been extended to many regions,[648] e.g. the Great Barrier Reef, Malaya and Florida. Davis,[649] whose standard work championed Darwin's theory of regional subsidence, accepted Daly's theory for the marginal belt, five degrees wide, on the north and south sides of the Pacific coral seas and

in the Lesser Antilles which alone have cliffed features.[650] The absence of cliffed headlands behind barrier beaches and the existence of submerged atolls are among the circumstances which are difficult to explain by the theory. Several authors[651] have sought to combine the main elements of the two theories.

There were apparently two cold marine periods (cf. p. 923), an earlier one at the close of the Pliocene and the beginning of the Pleistocene (Sicilian) and a later one in upper Pleistocene time. During the latter period, the cold species failed apparently to penetrate the Mediterranean as they did during the Sicilian, though the more stenothermal forms disappeared and the eury-thermal species, e.g. *Spondylus* and *Purpura*, were reduced in size and ornamentation.

Oceanic circulation. The position and strength of the ocean currents were modified to an unknown degree—further investigation of the floor deposits will help to discover them, since by this means the existence of a Pleistocene South Equatorial Current has already been established.[652] Ice-sheets covered parts of the sea-floor and lowered sea-level by abstraction (see p. 1354); the ocean's salinity was raised[653]; and permanent high-pressure systems surmounted the ice in mid-latitudes and cyclone tracks and planetary winds moved equatorwards[654] (see p. 1134). Stimulated by the greater temperature and pressure contrasts between the latitudes, the planetary air-circulation strengthened the water-circulation,[655] especially the circumpolar current of the Southern Ocean and its off-shoots along the west coasts of the southern continents,[656] though the action may in some measure have been counterbalanced by the rise in the salinity of the sea from 3·5 to 3·7% that tended to slow down the deep sea movement.[657] The intensified trade-winds caused an increased upwelling of cold waters and a compression of the Equatorial Counter-Current[658]—the convergence of this current is very sharp, red clay occurring on the north and calcareous ooze on the south.

The changed currents may have carried the *immigrés du Nord* into the Mediterranean[659] or the marine mollusca, resembling those of the West Indies, which are found on the shores of St. Helena.[660] Westerly currents may have markedly cliffed the western sides here and in the Hawaiian Islands.[661] The cold currents, as exemplified by the Labrador Current to-day, doubtless caused a degeneration of the vegetation along the adjacent coasts and an enrichment of plankton and of fish where they met the warm waters.

The intensified North-east Trade winds (see p. 1136) forced more water from the Atlantic Equatorial Current to go south of the Brazil salient, so diminishing the volume of the Antillean Current and lowering the temperature of the Gulf of Mexico.[662] Cooled at its roots, the Gulf Stream which may even have lacked access to the Caribbean Sea[663] when the sea was *c.* 90 m lower, was still further chilled by waters issuing from the North American ice-sheet. Because of off-shore winds, melt-waters from the glaciers and the lower ocean level, it probably left the coast at Cape Hatteras and proceeded due east, being turned back westwards after crossing the ocean much farther south than now so that little passed into the polar basin—cores in the ocean floor should give the amount of deflection of the Gulf Stream and the shift of the "arctic convergence". The Gulf Stream sent a branch southwards from about the south of Ireland and the Bay of Biscay and drifted icebergs to 29° N. Lat.[664] (see p. 1098). The cold Labrador Current may

have been weaker[665] or, more probably, like the East Greenland Current may have come into existence now for the first time.[666]

These changes were independent of any that might have arisen by displacing the poles and shifting the positions of polar flattening and equatorial bulging.

While the ocean in lower latitudes is "anothermic" and cools downwards, polar and subpolar seas are "mesothermic", having cold waters above (−1° to −1·9°C) and below (−0·3° to −0·6°C) a massive intermediate layer of warmer and more saline water (1·7° to 1·9°C). The latter, which is of tropical origin and underlies the shallow waters of lower salinity formed by melting ice,[667] reaches the continental slope of the Antarctic and in summer the front of the shelf-ice—it brings tropical plankton into the Weddell Sea.[668] The cold, heavy bottom water (Antarctic Circumpolar Water), which flows at 2·2 cm/sec[669] and feeds the bottom waters or ocean stratosphere in the tropics, is largely of Antarctic origin—the shallow submarine ridge across Davis Strait and the Wyville-Thomson Ridge largely prevent the entry of similar waters from the Arctic, the arctic bottom water being restricted to the Labrador basin and in still weaker development to the Spanish basin.[670] It is formed by cooling, freezing and convection on the continental shelf,[671] especially in the Weddell Sea, whence the bottom current (temperature −1·95°C; salinity 34·7‰) spreads eastwards round the whole of the Southern Ocean and into the west and east basins (where, because of its low temperature and salinity, it accounts for their lime-poor sediments[672]) and as far north as the Bay of Biscay[673]—the bottom water of the Ross Sea is unable to escape because of a submarine ridge (Pennell Bank).[674] In the Indian Ocean the red clay coincides roughly with its distribution.[675]

The "Antarctic Convergence"[676] (Oceanic Polar Front), or line along which the heavy, diatom-rich Antarctic surface water ("polar water") meets the lighter sub-antarctic upper water (temperature, 8–9°C) of lower latitudes ("mixed water of the middle latitudes") is easily and precisely detected by thermometer, analyses and tow net,[677] influencing the distribution of plant and animal life, e.g. plankton, benthos, fish and even polyzoa and other bottom-dwelling creatures—bird distribution is also related to it: the diatom *Rhizosolenia curvata* is the best indicator of the southern limit of sub-antarctic surface water. The amazing wealth of phytoplankton—the numbers of some species often run into millions in a single haul—is due to the high concentration of nutrients and gases and the turbulence of the waters. The average difference of surface temperature between the two sides of the convergence is 2°C (4° and 6°C in summer, 1° and 3°C in winter), though the "range" varies in longitude. Its position, which lies very nearly half way between the Antarctic coastline and the extremities of each of the southern continents, is dependent upon the bottom configuration—one factor is the spread of cold water as governed by the melting of the ice and the vigour of the atmospheric circulation—has a regular seasonal change varying between 25–100 miles (40–160 km) and lies for the most part in 50° S. Lat. In its turn, the convergence determines the boundary between the diatom ooze and globigerina ooze which lies just north of the convergence and approximately parallel to it and conforms with the trend of the normal limit of the pack-ice which lies within it (see fig. 19, p. 77). The Antarctic surface water here plunges abruptly to a deeper level as the Antarctic intermediate water (temperature, 3–7°C). The sharpness and constancy of position of the convergence, which

are in marked contrast to the fluctuating margin of the drifting ice, are now known to be governed by the latitude of the steeply upward climb of the warmer deeper water above the Antarctic bottom water (fig. 215).

Ross Sea has a northern wall so high (see above) that the deep warm current does not enter, the sea, especially in the south-west, being filled with extremely cold and salt Antarctic water (the coldest and heaviest water in the Antarctic)—the temperature is as low as $-1{\cdot}94°C$ and the salinity $34{\cdot}87‰$—so that its fauna has its peculiarities.[678]

The Antarctic Convergence divides the antarctic region to the south from the subantarctic region which stretches northwards to the Subtropical Convergence (Antiboreal Convergence of S. Ekman) where the surface tropical

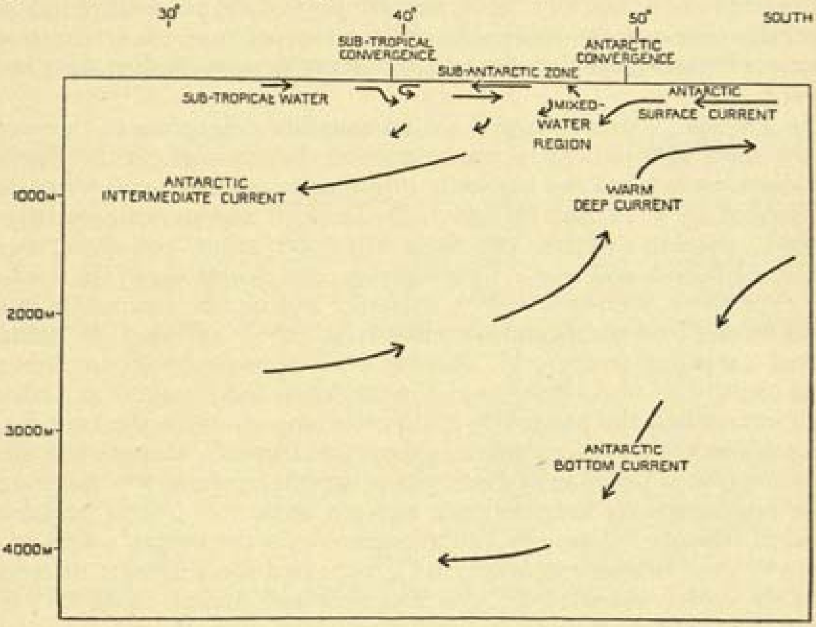

FIG. 215.—Vertical circulation of water in the South Atlantic Ocean; vertical scale exaggerated 550 times. G. E. R. Deacon, *Q. J. R. M. S.* 71, 1945, p. 15, fig. 1.

water finds its limit—this convergence is less sharp, especially in the eastern half of each ocean, and may be better termed a region of convergence.[679]

During the Glacial period the Antarctic Convergence was thrust northwards through about 10° to 50° S. Lat. Thus the lower layers around the Antarctic continent had less lime; glacial deposits spread beneath the modern diatom ooze and this beneath the globigerina ooze; and red clay underlies a globigerina ooze of later date and has a more southerly distribution[680]: cores in the floor of the south-east Pacific Ocean reveal a repeated oscillation of highly calcareous ooze and red clay, low in carbonate, to be correlated with three glaciations (with their various substages).

From what has been already said (see p. 1086) it appears that the Glacial period cooled the bottom waters of the oceans[681] and for the first time reduced their temperature by about 10°C to approximately the temperature of 1·8°C which reigns there to-day. It compelled the cold waters, a true cold relic, to creep into the abyssal basins of the tropics and dominate the circulation as a whole.[682] By dissolving the lime of the sea-floor it produced for

the first time in Cainozoic history the red clay[683]: it also carried oxygen to the depths so that the plankton sinking there no longer decays as formerly.[684] T. C. Chamberlin[685] thought it reversed the oceanic circulation which had previously had descending saline currents in tropical regions because of the high temperature—this, however, is unlikely since evaporation was then less active than now and the bottom saline waters would not rise in polar regions. However, by annihilating much of the preglacial fauna of the deeps, it may have led to the evolution of the present abyssal fauna[686]—the fish fauna which contains no single representative of an ancient family consists of highly specialised members of young families. This relict corollary of T. C. Chamberlin's main thesis is disputed since the fauna is of high antiquity and corresponds with present conditions.[687] Moreover, the present deep-sea fish fauna contains Palaeozoic and Mesozoic relics[688] and evolved from lower Cretaceous ancestors[689] (see above) while the bulk of the fauna sprang from a warm littoral fauna.[690]

The Ice Age, which enhanced the temperature differences of the oceans and the zonal distributions increasingly discernible throughout the Tertiary, may also have induced the bipolarity of the polar marine faunas,[691] perhaps first noticed by J. C. Ross[692] and J. D. Dana,[693] and shown especially by plankton, annelids, worms, crustacea, salt-water mites, pterapods, stenophores, amphipods and certain littoral groups, and doubtfully by the deep-sea life. The shark, *Lamna cornubica*, is bipolar and bipolar disjunction is also known among land plants and animals (see p. 1086). While J. D. Dana[694] invoked a separate creation, H. Théel's "relict hypothesis"[695] ascribed this faunal identity or similarity of species in the Arctic and Antarctic to a cooling which interrupted the previously continuous range through the latitudes by extinguishing the Tertiary species in the warm tropics. Darwin and others have also invoked a cooling in the tropics to explain bipolarity[696]: the majority of the bipolar species are temperate and not arctic.[697] Others postulate a spread of "bipolar" forms by "submergence" via the deeper waters of the tropics[698] (= "bipolar-epiplanktonic"), as proved for a number of species, or via the colder waters of the west American and African coasts.[699] This migration hypothesis is more probable than Théel's hypothesis in its original form, though it too is obviously a relict hypothesis since it involves the extinction of species in lower latitudes. Another migration hypothesis supposes that forms which originated in warm equatorial waters migrated to polar regions.[700]

Each of these theories encounters serious objections. In the case of certain radiolaria, foraminifera, ascidians and siliceous sponges, the similarity or identity may have arisen by convergent evolution or independent adaptations to similar physical environments.[701] Competition with younger and more vigorous forms, rather than the glacial chill which probably did not greatly affect longitudinal distribution in lower latitudes, may have extirpated the forms in the tropics.[702] A solution of the problem demands thorough collecting throughout the entire region, satisfactory classification, and scrupulous systematic work, ideals not yet attained.[703] Although recent discoveries of connecting forms in the tropics have eliminated one after another of the alleged bipolar forms and bipolarity is unknown in some groups[704] (e.g. schizopods, molluscs, nemertines, tunicates, echinoderms, hydroids, corals, brachiopods, foraminifera, cephalopods and fishes), and rare in others (cf. p. 1387)—Théel's list of 200–250 is now reduced to 28 at the most—certain

species among the better-known groups are definitely bipolar: bipolarity is more common among genera and higher taxonomic groups than among species. The time of continuity probably varied; it was earlier in families than in cases of generic or specific identity.

Bipolarity is only one aspect of the larger problem of discontinuous distribution which includes that of the amphi-Atlantic boreal element and the North Atlantic–North Pacific element (see p. 1089), both of which concern latitudinal distributions.

(*b*) *Drift-ice*

The limits of the pack-ice during the Glacial period were pushed farther equatorwards.[705] In the northern hemisphere, the Bering Sea was probably filled with pack-ice which extended to the Aleutian Islands where the warm

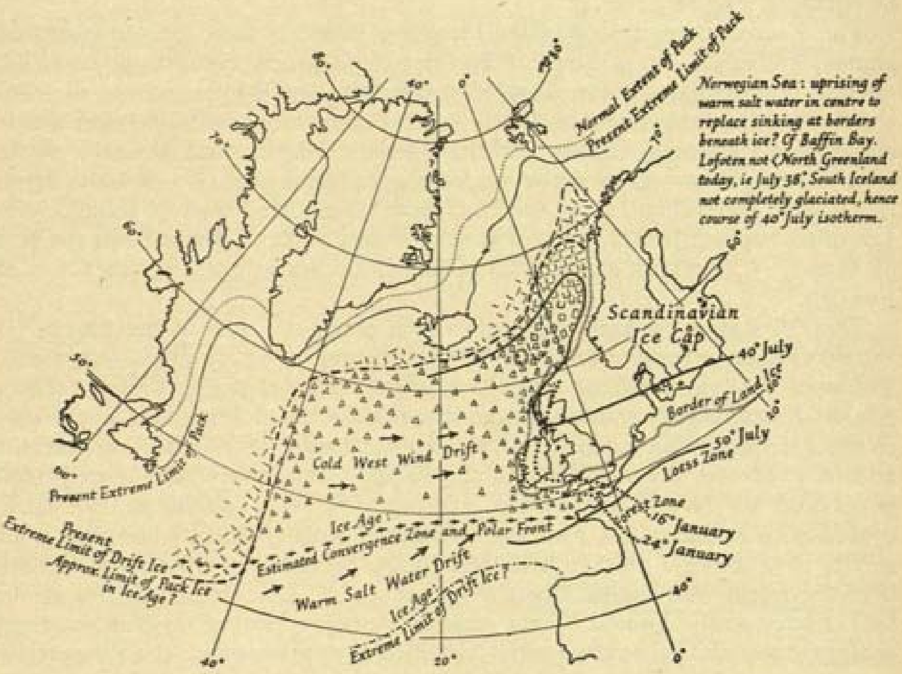

FIG. 216.—Pleistocene conditions in the North Atlantic region. G. Manley, *1074*, p. 62, top fig.

Japanese Current (Kiuo Siwo) fixed a limit; the North Atlantic had pack-ice which spread southwards to the north side of the displaced Gulf Stream (see p. 1134), i.e. south of Newfoundland and of Greenland, to south of Iceland and the north-west of the British Isles[706] (fig. 216). Icebergs were calved in greater numbers from both sides of Greenland, from Labrador and from the Grand Bank of Newfoundland to New York.

Winds from glacial anticyclones and marine currents carried drift-ice and thaw waters across the oceans. Erratic material was thus conveyed on a vaster scale than now.[707] *Galets exotiques* of gneiss, granite, pegmatite, porphyry, amphibolite, arkose and other rocks, mostly angular in shape and

now immobile, were rafted by coast-ice from Brittany, Cornwall and the Channel Islands over the bed and along the English and French coasts of the English Channel[708] and through the Straits of Dover into the North Sea[709] and the Low Countries—in exceptional winters coast-ice in the Channel to-day imprisons pebbles in this way.[710] Up to several tons in weight—the Giant's Rock, west of Porthleven Harbour, is a microcline gneiss weighing 50 tons—they were associated with clays bored by large arctic *Pholas crispata*, whose crypts contain the northern cirriped *Balanus poractus*.[711] Found in the Monastirian and Flandrian,[712] they belong to the Riss but mainly to the Würm glaciation.[713] Other debris was scattered off south-west England,[714] and boulders of igneous rocks resembling those of Scotland were conveyed to the Cornish coasts[715] (from Ross-shire and Argyllshire) and to Anglesey[716] (from Skye), and others of Kentallenite found their way to Greenock.[717] Chesil Beach contains pebbles of granite and porphyry resembling these rocks in northern England.[718]

The Faeroe Bank and Wyville-Thomson Ridge[719] have yielded glaciated stones, embedded in a kind of boulder-clay, which comprised Lewisian gneiss, Torridonian arkose, Cambrian quartzite and Moine schist, all from the Scottish mainland or a northerly extension, together with Old Red Sandstone from Caithness, Orkney and the Shetland Islands, and Mesozoic rocks from outcrops known to occur under the adjacent seas.[720] Erratics from north-west Ireland and west Scotland were transported west of Ireland, e.g. 150 miles (240 km) south-west of Kerry,[721] and as far as Rockall and the Bay of Biscay.[722] Erratics also drifted in the Baltic Sea into the Yoldia Clays of Sweden.[723]

The *Challenger* dredged up erratics west and north-east of the Azores.[724] Single ones have been obtained by the *Challenger* (1873–5), *Blake* (1877–80), *Talisman* (1883), *Valdivia* (1898), *Michael Sars* (1876–8), *Triton* (1882), *Knight-Errant* (1880) and other expeditions from the globigerina and red clay of the Atlantic as far south as 33° 47′ N. (north-east of Madeira) on the east and to 36° N. on the west.[725] In the Pacific Ocean, they have been traced as far as 28° 23′ N. off California.[726] Ice-rafted pebbles, cobbles and boulders, coated with a manganese film and associated with sediments showing poor sorting and mineral grains quite fresh, have been dredged from sea-mounts over the north-east Pacific Ocean down to 45° N. Lat.,[727] i.e. an area about half as large as the United States, and the southern limit of the diatomaceous sediment was shifted southwards. Erratics were floated into the Pleistocene marine clays of the Columbia and Williamette valleys of North America.[728]

Granules and pebbles up to 2 cm in diameter of various sedimentary, igneous and metamorphic rocks, obtained by coring in the North Atlantic (see p. 921), reveal that for long periods detritus-laden ice drifted at least as far south as 50° N. but not into the tropics, though pelagic foraminifera in the sediments prove that the ice was not a close pack but was open and drifting and probably melting rather actively.[729]

That Antarctic bergs drifted farther north during glacial time was proved by the *Challenger*, *Gauss* and *Meteor* expeditions. Erratics were dredged, for example, between Tristan da Cunha and the Cape of Good Hope, and in the Pacific from positions situated 10° of latitude north of the present limits of drift-ice. Patagonian bergs discharged their cargoes in places along the South American coast.[730] The difference, however, was far less than in the North Atlantic.[731] The waters were also colder.

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